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Symposium on Coordination of Power and Telephone Plant*

Introductory Remarks

By R. F. PACK

I UNDERSTAND I am expected to outline shortly what has led to the splendid cooperation between the Associated Companies of the American Bell Telephone System and the Power Companies of the United States in the matter of coordinating their facilities to avoid interference with the service of either.

Previous to 1921 disputes of a very serious nature were constantly occurring between the Bell Telephone Companies and the Power Companies, the former claiming that the rapid construction of transmission lines by the latter was seriously interfering with telephone service. The Power Companies felt that they also had a duty to serve the public and resented the attempts of the Bell Companies to interfere with the Power Companies' growth and progress. These disputes were so acrimonious and the parties to them so bitterly disposed towards each other that the courts and public service commissions in the various states were more and more frequently called upon to adjudicate the differences.

In the latter part of 1920 it was evident that the situation was becoming a serious menace to both great interests and suggestions were forthcoming from certain individuals representing both interests that attempts should be made to find a solution. Unfortunately, the names of those responsible for this constructive thought are not known and they cannot, therefore, personally be given their due meed of praise, nor assigned their proper places in history. However, as a result, early in 1921 a group of power men met with a group of Bell Telephone men, under the neutral chairmanship of Mr. Owen D. Young and there was then formed a permanent committee which has since been known as the Joint General Committee of the National Electric Light Association and the Bell Telephone System.

* Joint work of the National Electric Light Association and Bell Telephone System. Presented at the Winter Convention of the A. I. E. E., New York, N. Y., January 26–30, 1931.

This General Committee asked Mr. Bancroft Gherardi, Vice President of the American Telephone and Telegraph Company, and myself to select a Subcommittee of Engineers representing both interests, whose duty it should be to classify the types of physical situations in which engineering or technical conflicts were arising between the two interests and to indicate how on the basis of the existing state of the art the electric light and power engineers considered such situations should be met from a physical standpoint and how the telephone engineers considered such situations should be met without regard to the question of division of costs.

We requested this Subcommittee of Engineers to approach the various problems outlined in the broadest possible spirit of cooperation bearing in mind that the object to be attained was the removal of friction and the early development of mutually satisfactory standards.

Nearly a year later, in March 1922, Mr. Gherardi and I made our first report to the Joint General Committee based on the conclusions of the Subcommittee of Engineers.

Certain general statements were agreed to as for instance that the National Electrical Safety Code provided an acceptable guide to practise and that there were substantial advantages to both utilities in the employment of jointly occupied poles where conditions and character of the circuits permitted. It was also recognized that the public's interest was paramount and that both the power and communication utilities must be able to render their respective services to the public in an economical and efficient manner. A few general principles for the solution of inductive interference situations were suggested such as cooperative planning of all new construction and the further recommendation that standards of construction and operation in accord with the general principles outlined should be prepared and agreed to by further cooperative work of the Subcommittee of Engineers, and finally that a cooperative study of the art should be made in order to determine what practicable measures, if any, might be developed and adopted to lessen the contributing characteristics of both systems in this matter of inductive interference.

Mr. Gherardi and I in reporting to the Joint General Committee stated we believed great progress had been made and we urged that the General Committee advise the power companies and the associated companies of the Bell System to use every effort to arrive at a settlement of their differences through negotiations rather than resort to court or commission proceedings. It will be noted here that after one year we had made apparently but little progress in the actual solution of the problems involved. As a matter of fact, we know now that the foundation stone had then been well and truly laid. It was not so much what had actually been accomplished that mattered but that the whole spirit of the relations between the telephone and power interests had been completely changed from one of friction, distrust, suspicion and even of enmity to one of confidence, good will and a desire on the part of both to cooperate.

From that time the work progressed much more rapidly and in December 1922 a reasonably complete set of principles and practises for the inductive coordination of power and telephone systems had been agreed to and sent to the member companies of the N. E. L. A. and the associated companies of the Bell System over the signature of the Joint General Committee of which, as I have stated, Mr. Owen D. Young is Chairman. Since that time further reports containing principles and practises for the joint use of wood poles and the allocation of costs of coordinative measures have been agreed to and promulgated by the Joint General Committee.

Today inductive coordination as between the Bell Telephone System and the power companies is no longer a problem but only a routine day to day job of cooperatively continuing research work and developing the art of both systems to eliminate as far as possible causes for inductive interference.

I remember Mr. Gherardi once made the statement that the term "problem" is generally applied to a thing where you do not know the answer—"job" where you do know the answer to it and it is just a question of working on it—and it is exactly at that point we have arrived today. I do not mean to say we can remain quiescent as to this work because it is still a big job and will require the attention of the executives of the companies concerned and the constant and concentrated effort of the engineers of both interests who are engaged in research and other necessary work connected with inductive coordination.

To have had some part in bringing about these results has been one of the most satisfactory things I have done in my entire life and I believe Mr. Gherardi will fully coincide with this viewpoint as far as he is concerned. From the time I first met him, we have never departed from our belief that the problem could be solved on the basis of entire confidence, good faith and complete cooperation.

In the first instance we had many disappointments and some difficult situations to combat but I can truly say that we never had a serious disagreement and always were confident that the goal we desired would eventually be reached. I remember making a statement in those early days that I did not believe that each utility had obtained everything that each utility wanted but that I was confident that both utilities had got what both utilities wanted, and that a problem of this kind could not be settled by one party to a dispute getting all its own way because then nothing was settled. The trouble would simply be aggravated, making it more possible for controversies to arise again and again. I added that at no time had there been any question of compromising on principles, nor bargaining across a table,—we have had always before us a clear recognition of the problem of the other side and a mutual admission of the fact that the other system must live and that the primary interest is the public's and that the public must efficiently and economically be served by both utilities.

It may be of interest to you to know that the power companies with the same personnel on a General Committee, also headed by Mr. Owen D. Young, are now carrying on similar cooperative work with the Western Union Telegraph Company and with the Railroads with respect to their signal systems. The result of our cooperative work with the Western Union Telegraph Company will, of course, favorably affect our relations with the other telegraph companies of the country, as our work with the Bell System has affected in a highly satisfactory way our relations with the independent telephone companies of the country.

May I in conclusion thank you for the privilege of making this statement. It has been a particular pleasure to me because I am more and more convinced that this is the sound way to settle such problems and controversies arising between great interests in this country. Courts and regulating authorities approve this method because it promotes harmony and permits them to devote their time and talents to other useful purposes and because it saves the taxpayers the material expense of costly technical hearings in which the interests of the public are in no way jeopardized.

Trends in Telephone and Power Practise as Affecting Coordination *

By W. H. HARRISON and A. E. SILVER

The general trends in telephone and electric power systems are outlined and the reactions of certain of these trends on coordination are described.

In the telephone system, brief mention is made of the rapid growth of the dial system of operation, improvements in subscriber-station apparatus, rapid extension of new types of facilities for toll circuits and the growth of connections to foreign countries. Improvements in telephone service increase the importance of securing adequate coordination. The advantages of the use of cable facilities for toll circuits, of repeaters, of carrier current systems as regards coordination of long distance and interurban telephone circuits are discussed. The benefits accruing from improved subscriber-station apparatus, central office equipment, abandonment of iron wire for the short tributary toll circuits and new methods of making sleeves at joints in open wire lines are outlined.

In the power system, brief mention is made of increasing use of larger generating units, and growing use of automatic devices to replace manual operation. Improvements in power service generally react favorably on coordination. The general trends toward higher voltages for transmission and distribution and the improved standards of construction accompanying these trends are described. The important matter of system stability and the practises as regards grounding of transmission circuit neutrals, lightning control and current limiting devices, and the reactions of these matters on coordination are outlined. Reference is also made to grounding of distribution system neutrals, service taps on transmission lines, general practises as regards transformer connections and improvements in wave shape in so far as these matters react on coordination.

In conclusion, it is pointed out that, while there have been influences working both favorably and unfavorably toward coordination, the preponderant trend is definitely toward an improvement. The benefits which have accrued from the activities of the Joint General Committee and the important function of the Joint Subcommittee on Development and Research are also mentioned.

General Trends

THE important benefits resulting from the cooperative handling of questions arising from the proximity of the physical plants of the telephone system and the electric power systems of the United States are emphasized when consideration is given to the extent and the rapid growth of these two industries. This growth is illustrated by Fig. 1 which shows that during the past decade, while the population of the country has increased 16 per cent annual telephone messages have increased 96 per cent and annual kilowatt hour usage of power 107 per cent. Another indication of the growth of these utilities is given by Fig. 2 which shows that during the past decade customers telephone

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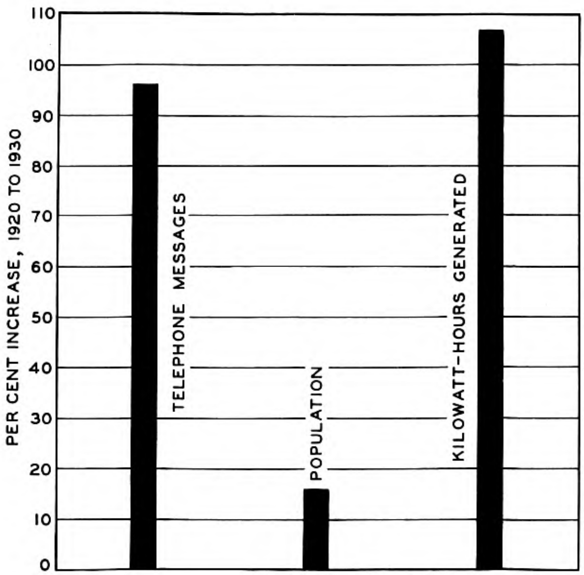
stations have increased 88 per cent and customers of central stations 127 per cent. The leaders of both utilities confidently expect that, apart from temporary setbacks associated with recessions in general business, the recent rapid growth of these utilities will continue throughout the next decade.



1930	Population.................	123,900,000
	Telephone messages.........	21,600,000,000
	Kw. hours generated........	90,000,000,000

Fig. 1—Per cent increase, 1920 to 1930, in population and in telephone and power usage.

Note: Values for 1930 are estimates based on best available data. Telephone data refer to Bell System.

Such a rapid growth of the two utilities both of which must supply the same customers with services essential to their comfort and prosperity, necessarily brings with it a large number of cases of physical proximity between the plants of the two utilities where, due to the widely different characteristics of the circuits involved, difficulties may arise. The necessity for active study of the coordination of the different systems and for the current handling of large numbers of individual situations will continue for a long time to come.

Associated with this rapid growth there has been another trend in these two utilities which has an important effect on coordination work.

This trend is the steady improvement in the quality of service afforded to their customers.

In the telephone system the improvement in the standards of service, if considered by itself, tends to increase the noticeability and the reaction on service of inductive effects from outside sources. Such changes as the improvement in the characteristics of transmitted speech, including the extension of the band of frequencies efficiently transmitted, and the avoidance of cases in which interfering noises are produced from sources within the telephone plant, tend to increase

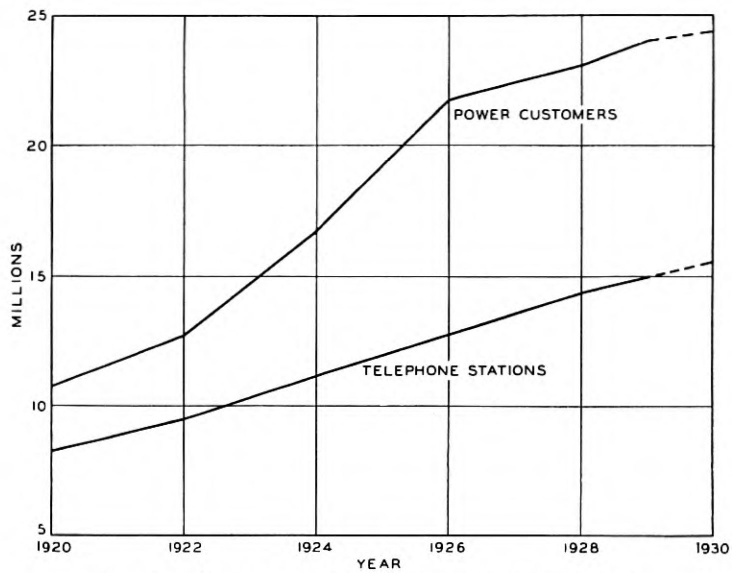


Fig. 2—Telephone station and power customer growth.

Note: Values for 1930 are estimates based on best available data. Telephone data refer to Bell System.

the effect of moderate amounts of noise current induced in the telephone circuits from outside sources. Similarly increases in the extent of the service and in the speed of completing calls have led to increased reliance on prompt telephone communication which tends to increase the importance of avoiding interruptions. Five years ago the average interval of time between the placing of a long-distance toll call by a subscriber and the commencing of the conversation was 7½ minutes. At the present time it is a little less than 2½ minutes. Telephone users have now come to rely on the almost immediate establishment of telephone connections and are correspondingly more critical of interruptions or delays.

The improvement of service has been associated with a particularly rapid growth of very long haul telephone business and a consequent increase in the average length of telephone circuits used for interurban and long distance work. This is illustrated by Fig. 3 which shows the

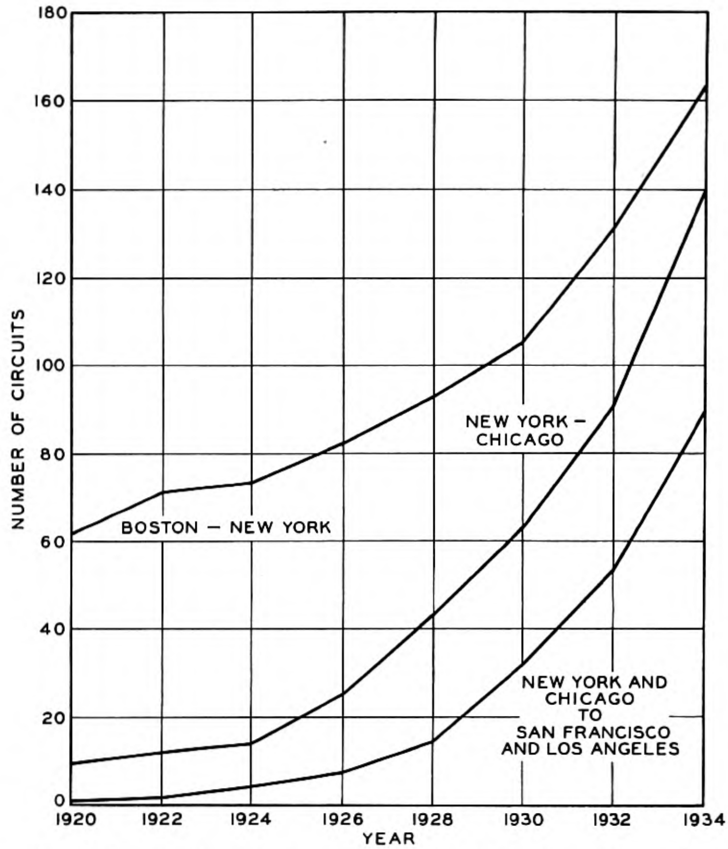


Fig. 3—Long haul telephone circuit growth of typical circuit groups.

growth in the last few years and the expected growth for the next few years of typical circuit groups of different lengths. In the period 1925 to 1929 while telephone toll business as a whole increased 59 per cent New York-Chicago business increased 170 per cent and the combined Chicago and New York business to Los Angeles and San Francisco 380 per cent. From the standpoint of coordination with other electric circuits the very long telephone circuit offers a more difficult problem than the circuit of moderate length because of the cumulative effect of exposures in different sections.

In the power industry one of the most important items in the improvement of service has been the steady decrease in the number of service interruptions. This has been brought about mainly by better standards of construction, including more systematic mechanical and electrical arrangements of circuits and apparatus, and increased numbers of circuits and sources of supply. The interconnection of power systems has figured largely in the last mentioned factor contributing to service reliability, by making available greater numbers of sources and by multiplying the routes over which power can be recieved at specific locations. While the increasing numbers of interconnecting and other types of lines bring new conditions for the coordination of power and telephone plants, improved construction and increased security of circuits and apparatus have a definitely beneficial effect upon matters of coordination by reducing the number of abnormal conditions of operation.

Other items in the improvement of the service given by the power industry are better voltage regulation and a great increase in the number of types of power consuming appliances and apparatus made available for the customer. Accompanying better voltage regulation are certain factors which definitely aid coordination, among these being better balance of currents in the separate phases of the circuits and more effective arrangements minimizing the tendency for currents to flow in the earth. The effect of increased numbers of types of utilization apparatus on coordination is problematical, though probably not of sufficient magnitude to be of practical importance.

Other trends which have a bearing on the improvement of power service are discussed in the section of this paper devoted to the power system.

While in some respects the general trends indicated above, namely, the extent and rapid growth of the two utilities, and the improvement of service standards, have by themselves tended to increase the importance and the difficulties of coordination work, these adverse tendencies have been offset by beneficial effects of improvements in plant design and construction and by the cooperative endeavor which has been carried on by the two utilities during recent years. It is a tribute to the effectiveness of this cooperative work that the degree of satisfactory coordination between the two systems is steadily improving. Fig. 4 shows that during the past 10 years the mileage of telephone toll circuits has increased 250 per cent and the mileage of power transmission lines over 100 per cent. The effect of such growth on the number of situations of proximity is illustrated by the fact that during the past three years the exposures of interest from a noise standpoint have increased from the equivalent of about 10 miles to about 14½ miles per 100 miles of open-wire telephone toll lead; while on the other hand the exposures not as yet adequately coordinated have in the same period decreased from the equivalent of 2.6 miles to 1.5 miles per 100.

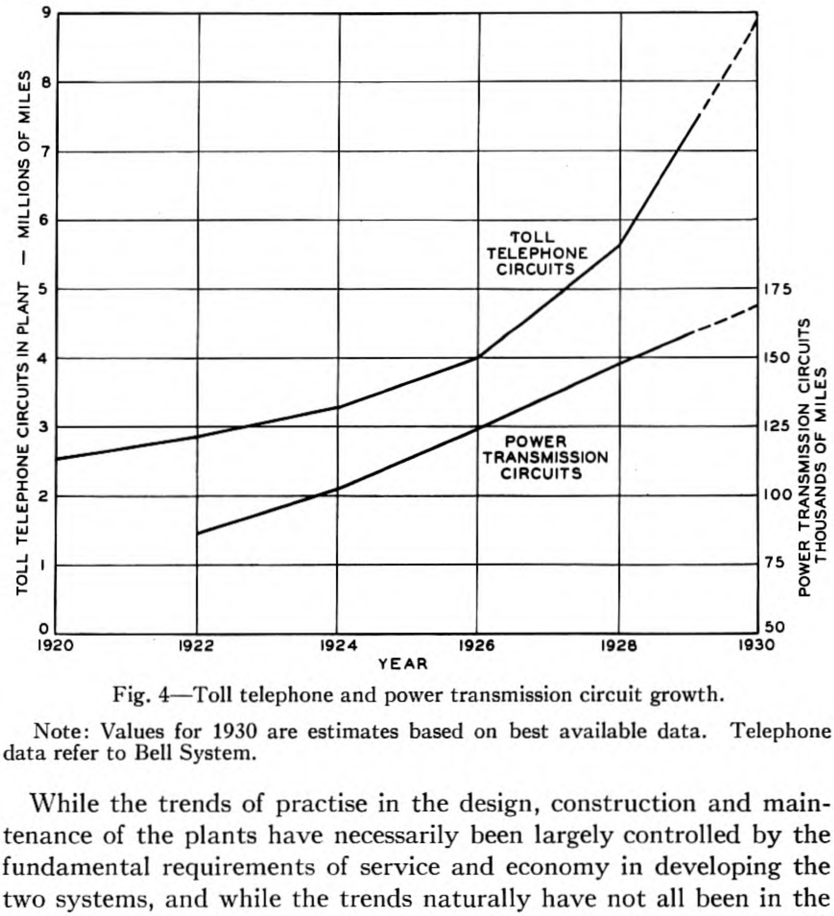


Fig. 4—Toll telephone and power transmission circuit growth.

Note: Values for 1930 are estimates based on best available data. Telephone data refer to Bell System.

While the trends of practise in the design, construction and maintenance of the plants have necessarily been largely controlled by the fundamental requirements of service and economy in developing the two systems, and while the trends naturally have not all been in the same direction as regards their effect on the coordination problem, still the general trend of plant practise at the present time is in the direction to facilitate the coordination of the plants of the two utilities. In the following pages brief statements are made, descriptive of the more important of these trends in the respective systems.

Trends in Telephone System

The telephone plant is at the present time rapidly changing in its physical character through the application of important developments and changes in engineering and construction practise.

Probably the most fundamental and far reaching of these changes is the progress of conversion from manual to dial system operation. When present plans are completed this will result in the operation of approximately 80 per cent of the telephones of the Bell System on a dial basis, and a large part of the existing manual central office equipment will have been removed from service. With the application of the dial system there is a trend toward a greater concentration of central office equipment in one building, so that in the future as many as 100,000 telephones may be switched by the various central office units in a single building. While these trends are of the greatest and most fundamental importance from the standpoint of the development of the telephone business they do not affect the coordination problem in any material way and therefore need not be further discussed here.

An important trend in telephone practise has been the provision of apparatus designed for higher standards of service and greater convenience for use at the customer's station. This includes the hand set, new types of private branch exchanges and of auxiliary telephone station apparatus, and improvements of transmission characteristics. These changes in some respects affect the coordination problem and these effects are indicated below.

Another important fundamental change in the telephone plant and one of great importance from the coordination standpoint is the rapid extension of new types of facilities for toll circuits, that is, long distance and interurban circuits whose use involves what is called a toll charge. These changes and their effects on the coordination problem are discussed in this paper.

One of the most spectacular trends of development of the Bell System at the present time is the increase in the number of connections to foreign countries. Earlier connections to Canada and Cuba were supplemented in 1927 by service to Mexico and by transoceanic radio links providing service from New York to London, through which connection is made to the principal European countries; and in 1930 a similar radio link from New York to Buenos Aires through which connection is made to Montevideo, Uruguay, and Santiago, Chile. During the next few years it is expected that these foreign connections will increase to include generally all important points in South America, Australia, Japan, Honolulu and all other points which may offer an appreciable demand for service.

These intercontinental circuits are not of such character and location as to be directly affected by the physical proximity of power circuits, but their efficiency is affected by the noise currents on connected circuits in the same way as other very long circuits are affected and this is discussed briefly below.

Toll Cable.—The change in methods of designing and constructing toll circuits which is of greatest importance from the standpoint of general development of telephone plant is the great increase in use of cables for those circuits, including both the very long distance circuits and the shorter interurban circuits. This increase is shown by Fig. 5.

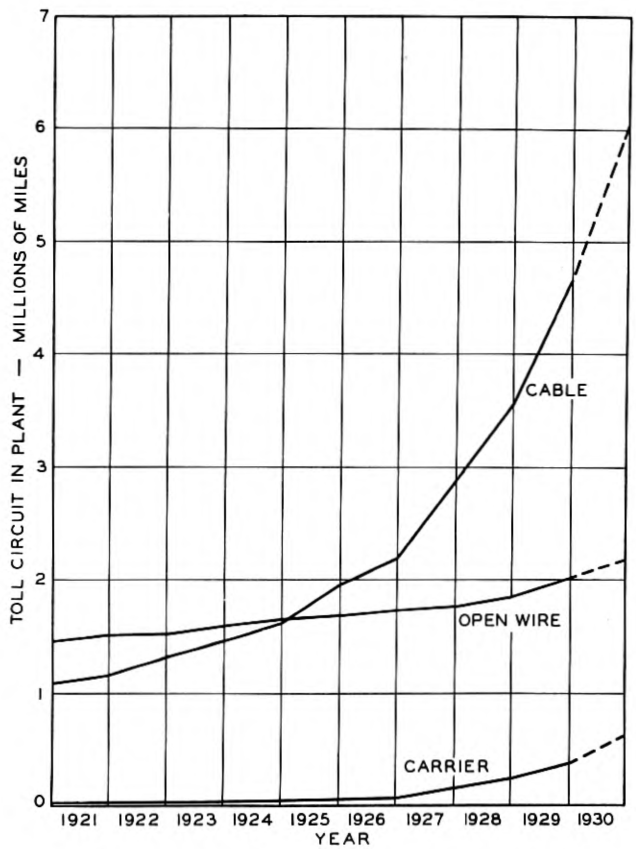


Fig. 5—Toll telephone circuit growth by classifications.

A single cable may provide for from 250 to 500 telephone circuits and several hundred telegraph circuits, that is, as many circuits as would be provided by five to ten heavily loaded pole lines of aerial wire construction. This concentration of circuits in a single cable, a number of which can be placed on a single route, is in itself of great assistance in coordination problems by greatly reducing the number of routes for which coordination arrangement must be made. Furthermore, the presence of the lead sheath, together with the twisting of the cable conductors, the high degree of balance with respect to ground, and the mutual shielding effect of the many circuits in one cable, practically prevents noise currents from being induced directly into the cable circuits from outside electrical sources. The shielding effect of the lead sheath when suitably grounded also provides substantial reductions in the voltages of fundamental frequency which may be induced along the cable conductors at times of trouble on neighboring power systems.

A telephone toll cable with its associated equipment costs about the same per mile as a twin circuit power transmission line of the 110-kv. class. This high cost has led to a large use of private right of way for new extensions of these cables, particularly for aerial cable construction. This, of course, has an added advantage from the coordination standpoint in tending to keep these important telephone routes off the highways, which are so much used for the distribution systems of both utilities. In the more rapidly growing cable routes underground conduit construction is employed and these in most cases are located along the highways. In these cases, however, the close proximity of several cables in the same conduit run offers a considerable amount of mutual shielding effect which reduces the susceptiveness of circuits in these cables to values approaching that obtainable by a single tape armored cable.

This tape armored cable, which recently has been placed in use in this country, is designed for burying directly in the ground, and has an increased degree of magnetic shielding. This is provided by two wrappings of steel tape outside the lead sheath which are necessary for the mechanical protection of the cable when ducts are not used. During the past year about 160 miles of this cable were installed and it is expected to have a considerable field of use in the future.

As indicated above, in all these types of cable construction the susceptiveness to noise induction is so greatly reduced that low frequency induction generally becomes the limiting factor relative to the permissible proximity of these cables to power circuits. The relative amounts of induced voltages with these different types of construction in comparison with open wire construction, while naturally varying with local conditions, are indicated in a general way in Table I.

TABLE I

Type of Construction	Approximate Relative Volts on Telephone Circuits per Ampere of Inducing Current at 60 Cycles
Open wire	1.0
Single cable, aerial or underground—sheath well grounded	0.5
Buried tape armored cable—well grounded	0.2

Note: All values for cables assume full size, i.e., 2⅝-in. diameter.

The above figures are based on favorable conditions for obtaining low resistance ground connections on the cable sheaths. Such ground connections are necessary to provide the full shielding benefits, since the shielding is brought about by induced currents on the cable sheath flowing along the sheath and through ground. These sheath currents, because of the close coupling between the sheath and pairs, induce voltages into the pairs tending to neutralize the voltages induced into the pairs directly from the power system. The use of the tape armor, which is a magnetic material, increases the coupling between the sheath and pairs. The grounding conditions necessary for satisfactory shielding effects can usually be obtained, but situations sometimes arise in the case of aerial construction where it is difficult or impossible to obtain them.

While as noted above, the cable circuits are effectively protected from noise induction, the efficiency obtainable over the long circuits is limited in part by the noise currents occurring in the open-wire lines which may be switched to the long cable circuits. This is because the efficiency of the long cable circuits depends upon voice-operated switching devices which must not be operated by the noise currents. This is also true of the intercontinental circuits mentioned above. The extension of the circuits controlled by voice-operated devices tends therefore to increase the importance of good coordination of the entire plant.

Telephone Repeaters.—Another important trend of practise is the extended use of telephone repeaters. The purpose of these devices is to amplify the voice currents and thus make possible higher efficiency and greater extension of long distance telephone circuits. Their use is essential to the great development of toll cable. Moreover, they are used widely on open-wire circuits. Without repeaters it was necessary on the long open wire circuits to permit the power level of voice currents to sink to relatively low values. An extreme example of this is given by the New York-Denver circuit which, before repeaters were available for use on this circuit, had an overall equivalent, using the highest grade of telephone construction which had been developed up to that time, of about 31 *db.*[1] With the application of repeaters to this circuit the level of voice currents could be kept relatively high throughout the circuit. This is illustrated in Fig. 6 giving level diagrams for the circuit as originally set up and later when provided with repeaters.

The use of repeaters contributes to reducing the susceptiveness of the telephone plant and thus aids coordination. On such a circuit as the original New York-Denver circuit just mentioned, a relatively

[1] This means that the ratio of output power to input power of this circuit is 0.0008.

small amount of noise current greatly impaired transmission because of the weak incoming voice currents. Although the repeaters naturally amplify the noise currents as well as the voice currents, the fact that the voice level is kept high throughout results in great benefit which in this case, assuming similar exposure conditions in the various repeater sections, gives an improvement in the ratio of voice currents to noise currents of slightly over five.

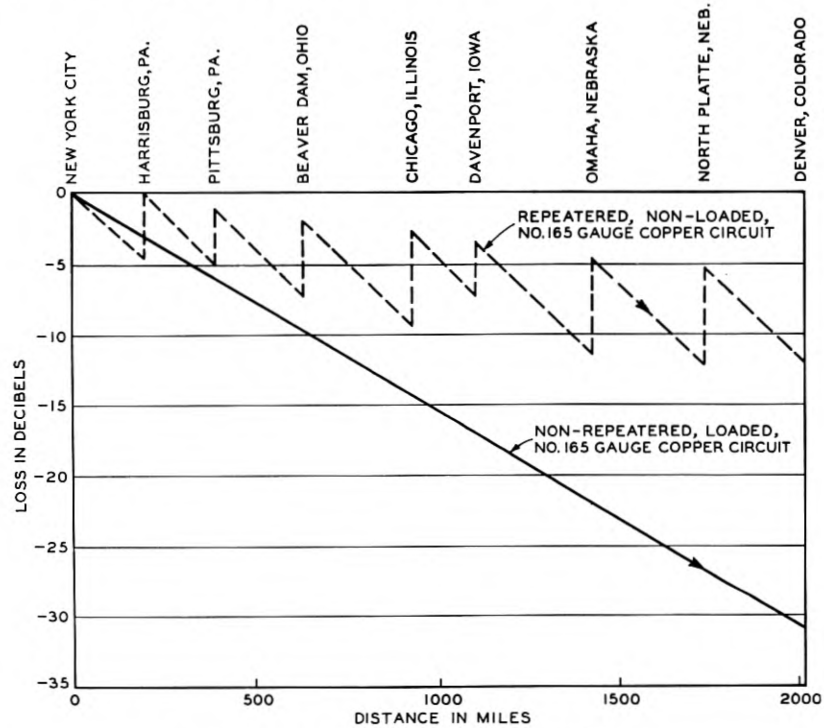
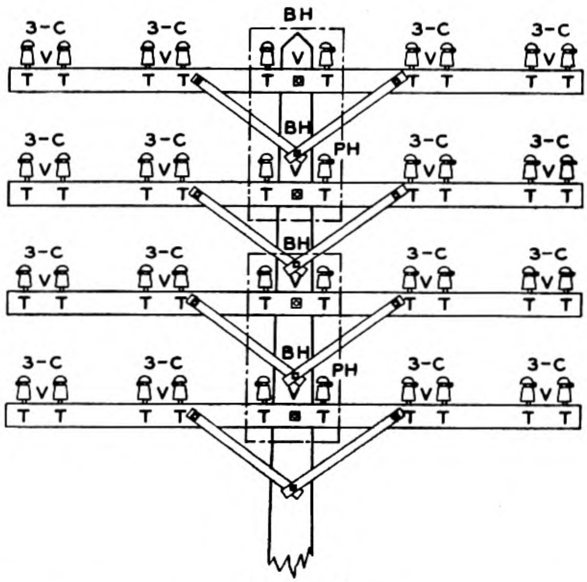


Fig. 6—New York—Denver circuit level diagrams.

Repeaters probably also have some effect in reducing certain of the effects of low frequency induction by the fact that they sectionalize cable lines at about 50 mile intervals and open-wire lines at intervals of 200 miles or less, and limit the power which can be transmitted from section to section. There is some evidence that this tends to limit acoustic shocks.

Carrier Telephone Systems.—A third important trend in telephone practise is the extension in the use of carrier telephone systems for long circuits and the associated changes in aerial wire construction practises. The growth in use of this type of circuit is indicated in

Fig. 5. The carrier systems are much less influenced by noise induction from power circuits because they occupy a range of frequencies (5000 to 30,000 cycles) in which the harmonic power voltages or currents ordinarily are extremely small. Furthermore, in order to obtain economies inherent in the use of large numbers of carrier systems on the same telephone pole line it has been necessary to design systems of



LEGEND

SYMBOL	FACILITY	TOTAL CIRCUITS	
V	VOICE FREQUENCY-PHYSICAL	20	
PH	VOICE FREQUENCY-PHANTOM	2	
3-C	CARRIER TELEPHONE	48	
T	D-C TELEGRAPH	40	
BH	CARRIER TELEGRAPH (10 CHANNELS)	40	
	TOTAL TELEPHONE		70
	TOTAL TELEGRAPH		80

Fig. 7—Pole line configuration.
Non-phantomed construction—8-inch spacing between wires of non-pole pairs.

transpositions of much increased effectiveness and even to change the configuration of the wires in order to greatly reduce the inductive effects between the telephone circuits. These changes also result in reduced susceptiveness to outside inductive influences. The type of construction now recommended for new aerial wire lines in cases where the extensive use of carrier is anticipated is shown in Fig. 7. The two wires of each pair, except pole pairs, are spaced 8 in. apart compared with the previous standard of 12 in. Often transpositions are made as frequently as every second pole and are of an improved type giving better balance between circuits; also on the circuits on which carrier telephone is used the phantoms are abandoned. The relative susceptiveness to noise frequency induction of the various types of aerial wire construction has been tested for various typical conditions. The results of these investigations are summarized in Table II.

TABLE II

Facility	Type of Transposition *	Approximate Relative Susceptiveness †
12 in. phantom	Voice (brackets)	1.00
12 in. side	Voice (brackets)	0.50
8 in. pair	Carrier (break irons)	0.25 or less

* Voice circuits are not so frequently transposed as carrier circuits. Bracket type transpositions require two spans to complete the transposing whereas the break iron type completes the transposing on a single crossarm.

† Susceptiveness is used in the sense defined by the Joint General Committee, namely, "Those characteristics of a signal circuit with its associated apparatus which determine, so far as such characteristics can determine, the extent to which it is capable of being adversely affected in giving service, by a given inductive field."

Subscribers' Station Apparatus.—To a large extent the trend of development in subscribers' station apparatus is toward new arrangements which provide greater convenience and more closely meet the needs of the users and which have no material effect upon the coordination problem. An important group of developments, however, centers about the improvement of the electrical performance of the station apparatus by removing impairments caused by the earlier types of apparatus. These changes, by improving the quality of speech as reproduced by the telephone system, tend to make more noticeable the impairments caused by the effects of currents induced from external sources.

The tendency toward an increase in the range of voice frequencies efficiently reproduced by the telephone system tends to increase the range of frequencies of induced currents which may cause noise interference as discussed in the introductory section. An extreme illustration of this is the circuits designed to transmit programs for radio broadcasting stations. The transmission characteristics of these circuits have been improved by including both higher and lower frequencies, and in their most modern form these circuits efficiently transmit currents of frequencies in the range between 35 cycles and 8000 cycles and are therefore capable of being affected by inductive noises over this wide range.

The room noise conditions at the subscribers' premises have an effect on telephone transmission. This noise besides acting directly on the ears of the telephone user is converted by the transmitter into electrical currents, a part of which actuates the receiver, thus producing noise. The present trend in telephone practise is very strongly toward a reduction of these effects. This will tend to bring into increasing prominence noise caused by induction in the telephone circuits which now in many cases is partially overshadowed by the reproduction of the noises in the room.

As partly offsetting this tendency steps have been taken to improve the degree of balance to ground of new station apparatus, particularly in the case of party lines. The new station apparatus with the improved transmission characteristics discussed above will be designed for reduced effect of noise currents entering from the line. Also, in extending the selective signaling features to rural areas, higher impedance ringers and a newly developed high impedance relay are being used in order to limit susceptiveness to noise from exposures between the rural open wire extensions and rural power distribution circuits. Where central office equipment is being modified to permit of increased range of direct current signaling, or for some other reason, the reduction of susceptiveness is always a consideration. All of the newer repeating coils used for supplying talking battery to subscribers in common battery areas, which comprise the bulk of the local plant, possess a much higher degree of balance than the coils which were standard a few years ago.

Other Items.—So far the changes which are associated directly with the major trends of development in the telephone plant have been described. The broad outlines of these developments depend on all of the factors affecting telephone service as well as coordination with power circuits. There are other features not directly associated with these main trends which, while introduced into the telephone plant largely because of the advantages to be gained in reducing susceptiveness to electrical influences, have also afforded other benefits. A few of the more interesting examples of these changes are given below.

Referring to the toll plant, there may be mentioned the recently adopted general practise of soldering aerial wire sleeve connections in order to insure a permanently high degree of series balance. Heretofore reliance had been placed on the contact between the wires and the twisted sleeve. The practise of soldering will be supplemented in the near future by a cold-rolled sleeve method, and it is confidently expected that these practises will result in material noise improvements. They will also probably reduce the maintenance required on open wire toll circuits, particularly where exposures are involved.

Another item is the abandonment of the use of iron wire and substitution of copper for short tributary toll circuits. Coordination of the iron wire circuits is relatively difficult because of the development of resistance unbalances at the wire joints. The transmission efficiency is also improved by the reduced resistance afforded by the copper but this effect is generally of secondary importance in the short tributary circuits.

In toll offices improvements have been made in the balance of coils and condensers used for superposing telegraph on the telephone circuits. The use of repeating coils, commonly used for side-circuits, has been extended to phantom toll circuits. These coils act as insulating transformers to prevent noise voltages from the outside conductors being impressed upon the intricate cabling and equipment of the office.

Referring to the local plant, there are several noteworthy examples of modifications made principally for the purpose of reducing susceptiveness. Investigation such as that of the coordination between power and telephone distribution plants conducted at Minneapolis by the Joint General Committee, stimulated the development of means for reducing the susceptiveness of the telephone distribution plant. Present practises call for the interconnection of aerial and underground cable sheaths and the grounding of the aerial sheath in order that the benefits of the shielding action of the sheath currents as previously described, may be realized for noise induction. In cases where electrolysis conditions do not permit direct grounding, condensers of the electrolytic type are employed to prevent the flow of direct currents.

The telephone circuits have long been equipped with over-voltage protectors for the purpose of protecting apparatus and cables against lightning waves and against power frequency transients from the lower voltage distribution circuits, also with fuses for opening the lines in cases in which heavy currents flow. The trend in development of these devices has been principally toward more uniform operation and lower maintenance costs. With the rapid increase of voltage and capacity of power circuits generally, experimental studies have been undertaken of further means for maintaining the safety of persons working on or listening on the telephone circuits. At the present time, development work is being done on various devices for this purpose, some of which are fundamentally different in design and operation from those previously used. It is hoped that these devices, which are discussed in one of the following papers, will afford increased protection against overvoltages and improve coordination conditions.

Trends in Power System

In the field of power generation marked attention has been paid, from the start, to methods of improving the efficiency of the generating process and reducing the investment per kilowatt of generating capacity. This has led to the development of larger and larger generating units. A single shaft unit of 160,000 kw. capacity and a triple-element unit of 208,000 kw. capacity are in operation. The latter consists of one high pressure and two low pressure turbines with their respective generators. Single shaft units of 200,000 kw. capacity are under construction and it seems probable that the trend in the future will be toward even larger units of both types. This trend toward larger units instead of the equivalent in small units has resulted in improved wave shape but otherwise does not directly affect coordination except in so far as it may reflect the general trend toward larger concentrations of power with the accompanying tendency to increased magnitude of system abnormals.

Another definite trend in the power industry, but one which is not of importance from the standpoint of coordination, is the increasing use of automatic devices to replace manual operation. Complete automatic operation is being practised to some extent in hydroelectric generating stations and is widely practised in substations of various types. The trend is definitely toward wider use of automatic devices and new types and applications of such devices are being constantly developed.

In view of the remarkable development and rapidly multiplying uses of thermionic tubes and related devices in other fields, and the theoretically potential applications in the power art, the question will doubtless be asked as to the trend of their application in the power field. However, other than application for current rectification, such as in railway work, it cannot be said that progress has advanced to the point of establishing a trend.

Those trends in power system development which are more directly concerned with matters of coordination are discussed in the following.

System Voltages.—Referring to Table III, it is of interest to note that the rate of increase of transmission line mileage, as a whole, is lagging behind the rate of growth of both installed generator capacity and electricity production. Furthermore, mileages of the higher transmission voltages, 220 kv., 132 kv., 110 kv. and particularly 66 kv., are growing at a faster rate than the group average. These comparisons reflect the increasing utilization of the higher voltages with the greater circuit capacities they provide. As power industry growth requires the handling of larger blocks of power and as greater distances between sources and markets are encountered, the development and use of circuits and apparatus to transmit at voltages higher than the 220 kv. initiated in 1923 must be expected as an economic necessity.

In the distribution field also, coincident with the development of rural service, there has been a movement to higher voltages in primary circuits, and indications point to the continuance of this trend in the future. Due to the distances involved, voltages from 6600 to 13,200 (and even higher) have been used in rural work. In urban areas the high load densities encountered in some districts require the handling of large blocks of power in the primary circuits, and the lower primary voltages have often been replaced by higher voltages for such conditions. In addition to the greater capacities provided by the higher voltages, possibilities of system simplification by combining rural and urban systems and eliminating voltage transformations are of considerable economic importance.

While at first glance the pronounced trend to higher transmission and primary distribution voltages may appear to enhance the difficulties of coordinating communication and power lines, certain factors enter to offset this. As transmission voltages increase, line construction as a whole becomes more massive, greater clearances and wider rights of way become necessary and construction costs per mile rapidly rise. These greater space requirements weigh against the use of highway locations and, together with the higher construction costs, which make the shortest possible lengths desirable from an economic viewpoint, frequently influence the selection of direct cross-country private rights of way providing generally greater separation from communication circuits in the same territory.

TABLE III

TOTAL CIRCUIT MILES OF TRANSMISSION LINES. BY VOLTAGES, YEARS 1926–1929 INCLUSIVE

Voltages	1926	1927	1928	1929	Per Cent of Total 1929	Average Annual Increase Per Cent 1926–1929
220,000	1,054	1,257	1,442	1,442	0.9	11.0
132,000	3,125	3,343	4,010	4,448	2.8	12.5
110,000	7,875	8,661	9,114	10,159	6.4	8.9
66,000	12,157	15,212	18,716	21,236	13.3	20.4
60,000	8,801	9,257	8,076	8,174	5.1	−2.4
44,000	7,517	8,492	8,732	8,761	5.5	5.2
33,000	23,831	24,706	27,451	28,523	17.9	6.2
22,000	10,130	10,429	11,545	12,583	7.9	7.5
13,200	19,496*	18,441*	19,551	21,340	13.4	3.1*
11,000	8,072	9,145	10,007	10,860	6.8	10.4
All other over 11,000	28,223	28,535	29,843	31,916	20.0	4.2
Total	130,281	137,478	148,487	159,442	100.0	7.0

* This apparent discrepancy is believed to be due to reclassification of these lines as between transmission and distribution facilities.

The use of the higher voltage circuits, each transmitting many thousands of kilowatts, of itself tends to increase the problems of coordination. However, the greater separations obtained by the use of private rights of way for these main transmission circuits in most cases eliminate the need for coordinative measures to control normal induction (manifested as noise in the telephone circuits) and, in case noise presents a specific problem, the greater separations simplify and render less extensive those specific coordinative measures which may be required. Induction due to power system abnormals too is mitigated or rendered easier of control.

In the case of distribution lines, the adoption of increasingly higher voltages is accompanied by more systematic grades of construction and greater clearances from communication circuits. The result, of course, is that fewer abnormal conditions of operation occur and the number of related disturbances in the communication circuits is correspondingly reduced. The possibility of contact between power and communication circuits is also reduced. This trend toward better grades of construction applies also to transmission lines and, as noted previously, to other parts of the power system.

System Stability.—During recent years considerable attention has been paid to the development of methods for improving system electrical stability. One of the most important of these methods is the use of higher speed switching,—at present, faults can be cleared in 15 cycles, or less, of a 60 cycle wave. So far, high speed switching has been applied mainly to transmission circuits. However, as development proceeds and cost of equipment required is reduced, the field of application of high speed switching may naturally be extended to distribution systems. The result in the case of either transmission or distribution will be, of course, to reduce the duration of transients. Akin to high speed switching, the use of high speed excitation of rotating equipment has been developed. This may tend to increase the maximum fault current values somewhat which would make coordination more difficult. However, the reduction in the severity of instability surges, in so far as such surges involve faults-to-ground, affords definite benefits from the coordination standpoint. It requires further study and observations to determine what, if any, inherent limitations or advantages it may possess with respect to coordination work.

The way has been paved for the development of high speed switching by steady improvement in relaying practise. Selective operation of protective relays in power systems, during the early stages of relay development, was largely dependent upon an additive sequence of time intervals which might aggregate a considerable period in the case of the more remote units in the sequence. The development of relaying practise has included various methods of securing selectivity independently of time. This has accomplished large increases in the over-all speed of operation, at the same time improving selectivity. Coincident with these improvements there has also been a substantial gain through greater precision in design and workmanship and improved application of relays and related devices. These trends definitely aid coordination by reducing duration of transients, eliminating faulty relay operation, and steadily reducing the radius of influence of system abnormals.

With the growth in power systems and major interconnections, the use of bus or feeder current limiting reactors or other means of limiting the concentration of fault current flow is being given increasing application. Such practise acts to restrict the magnitude of inductive transients. In distribution systems the growing use of feeder reactors has a similar effect in matters of coordination.

For well known reasons, among which are the avoidance of transient over-voltages resulting from arcing grounds and the economies made possible in apparatus insulation, it is predominant practise in America to ground the neutrals of transmission systems at important transforming centers, sometimes through resistors or reactors but usually solidly. In view of the prevalence of the latter method, a large proportion of higher voltage transformers now in service have been constructed with insulation between the neutral ends of the grounded windings and the core and tank, designed to support only the neutral potentials produced by fault currents regulating through the unavoidable impedance of grounding connections. The economies resulting from this method of construction become greater as rated operating voltages rise. The use of solidly grounded neutrals tends to make coordination more difficult in view of the possibilities for increased flow of earth currents.

On some large power networks with relatively great possible concentrations of short-circuit power and solidly grounded neutrals tendencies towards instability of operation have appeared. In some instances also oil circuit breaker characteristics, particularly as regards the older breakers in service, have become a source of concern. For these reasons, in these situations, increasing study and consideration are being given to the use of current limiting devices in the neutral where the characteristics of the apparatus and limitations of relaying will permit of such operation.

In some European countries, particularly in Germany, where grounding for the purpose of power system voltage stabilization is excluded by governmental regulation, dependence is extensively placed on the Petersen coil as a substitute. This device may be regarded as a special type of neutral impedance. The Petersen coil has been applied to but limited extent in this country although its possibilities for moderate voltage systems, especially for situations warranting only single circuit supply, are receiving consideration.

In this country, the increasing use of neutral impedance as well as the use of other types of current limiting devices is an aid to coordination since it reduces the magnitude of abnormal induction.

Lightning Control.—The major problem of the transmission art at the present time is the control of lightning in its effects on service. In those sections of the country in which lightning is prevalent, this natural hazard accounts for a large proportion of transmission circuit faults, approaching 100 per cent in the case of the heavier, higher class trunk transmission lines. The seriousness of this problem and the researches which some of the larger power utilities and apparatus manufacturers are conducting for its solution are being fully reported from time to time before the Institute and need not be discussed here. It is sufficient to say there is encouragement that methods for the solution of this problem, as it affects high voltage trunk circuits, will be known in the not too distant future. Where adequate methods are found and applied the results, of course, will be a decrease in the number of system disturbances which induce transients in communication circuits.

Present measures in power system practise, especially at the higher voltages, directed toward the control of service interruptions caused by lightning include improved application of overhead ground wires, improved grounding connections at the supporting structures, the improved use of wood for lightning insulation, and the use in shunt with line insulators of fused gaps or other valve devices to "spill" the surge without dynamic current follow up. There is also under consideration the application on grounded neutral systems of single-phase switching. All of these measures, with the exception of the last, are helpful from the coordination viewpoint since their effect is to avoid or reduce system faults or at least to decrease the magnitude of earth fault currents and hence of the accompanying voltages induced in nearby communication circuits.

Single-phase switching involves the use of individually controlled and operated single-phase circuit breakers. Upon the occurrence of a single-phase fault-to-ground, the breakers on the faulty phase only would open, leaving the other two-phase conductors in circuit to maintain connection momentarily between source and load. In a short interval the breakers controlling the faulty phase would be reclosed automatically.

Single-phase switching has not progressed beyond a preliminary consideration of its possibilities. If applied in situations of proximity, the residual voltages and load currents while one phase of a three-phase grounded neutral system is momentarily open circuited may constitute a problem in coordination.

Underground Construction.—The use of underground construction in distribution systems is seldom economical but is increasing in high load density districts and in some residential areas primarily due to requirements for civic improvements and the relieving of surface congestion. The reduced influence on communication circuits of such underground circuits as compared to overhead construction, is too well known to need repeating here. Coincident with the more recent developments in underground distribution certain special situations have brought about the development of underground cable suitable for use in high-voltage transmission circuits, inclusive of 132 kv. Underground installations involving these transmission voltages are highly special, comparatively few in number and small in extent. However, they have a definitely favorable effect upon coordination problems withing the territories surrounding them.

Aerial cable construction for both distribution and transmission circuits has been used to a limited extent and has a definitely beneficial effect upon coordination matters. Whether this type of construction will be extended in the future is not evident.

Grounding of Distribution System Neutrals.—One of the difficult tasks encountered in distribution systems is that of obtaining adequate grounding of primary and secondary circuits. Because of this difficulty the establishment of neutral networks grounded at many points has become a practise. In most cases in the past, two separate neutral networks have been provided, one for the primary and one for the secondary system. However, in several localities these two separate neutrals have been combined into a common-neutral arrangement providing in this way an increased multiplicity of ground connections to both the primary and secondary neutral conductors. Further extension of the use of this system is probable. This arrangement introduces features of interest from the coordination standpoint, because of the increased opportunities for the flow of currents through the ground. Experience and investigations so far, however, indicate that with adequate attention to coordination this arrangement is comparable in its effect on neighboring communication circuits, to other types of distribution systems.

Service Taps on Transmission Lines.—In some rural situations, it has been found economically impracticable to initiate distribution lines due to distances involved. However, in many such situations immediate electric service is urgently required and in some of these cases, transmission lines may be located relatively close to the point where service is desired. In such cases the only alternative to a long distribution line is to tap the high tension transmission line when this can be done by some less expensive method. Such methods have been developed and applied to a limited extent. More study and field experience are needed to determine the effects of these installations on inductive coordination should they become extensively employed.

Transformer Connections.—In distribution practise, the trend toward higher primary voltages has been accompanied by the use of the "Y" connection of the primaries of transformers as a step in the transition from one voltage class to another. Thus 2300-volt delta systems have become 2300/4000-volt "Y"connected systems, 6600-volt delta systems have become 11,000-volt "Y" systems, and the 7620/13,200-volt "Y" connection is being used. The use of the "Y" connection of the primary of distribution transformer banks is sometimes necessarily accompanied by a similar connection of the secondary. Such "YY" connections are usually in urban situations. Also, these banks usually represent only a small portion of the total transformer capacity on the circuits.

On large transformer banks and in the higher voltages delta-Y connections have long been the prevailing practise. However, where the "YY" connection is used for purposes of grounding, especial attention has been given to controlling the effects of this connection in situations of coordination, and for the absorption of triple harmonic currents it is common practise to use delta-connected tertiary windings in such installations. This subject is discussed more fully in another paper in this symposium.

Wave Shape.—The connection of primary circuits directly to generating station busses results in service and economic advantages by eliminating transformations thereby improving voltage regulation and aiding system simplification. This practise, however, tends to make coordination more difficult as those harmonics which may be present in the generated voltage can flow directly out over these circuits. However, the important bearing of the wave shape of generators and apparatus of various kinds on the coordination problem has long been realized and is receiving increasing attention. Even before the formation of the Joint General Committee the general problem of apparatus wave shape was being studied both as to the amounts of various harmonic components which were present in apparatus wave shape and as to the relative effect of these components when appearing in communication circuits by induction from power circuits. As a result of this study an instrument was developed for measuring "Telephone Interference Factor" of a voltage wave. With this instrument as an aid a better understanding of the bearing of wave shape has been gained by the apparatus manufacturers and there has resulted a gradual improvement in the wave shape of new apparatus.

It is recognized that there is a median line beyond which general improvement in the inherent wave shape of apparatus would not justify the attendant increased difficulties of design and increased manufacturing costs,—to avoid the alternative of applying in specific cases, available and less expensive methods of externally correcting wave shape. Work is now in progress cooperatively between the manufacturers and users looking toward the establishing of a measure of wave shape in apparatus design which will strike an economic balance between benefits and burdens.

The increasing use of rectifiers for conversion from alternating to direct current has an influence on inductive coordination. Considerable study has been devoted to this matter as result of which methods for control of the distortion of the d-c. voltage wave caused by the rectifiers have been applied in several instances and a solution of this part of the problem appears to be in hand. More study and experience are needed as regards the specific conditions under which the wave shape distortion of the alternating current supply would require consideration.

With the progress begin accomplished in the design and application of apparatus and the better understanding of the influence of circuit and transformer connections on inductive relations, problems concerned with wave shape can be expected to steadily decrease. The status of the cooperative study of this subject is described in this symposium.

Conclusion

A brief outline has been given here of the general trends in plant development and operating practise in telephone and power systems with special regard to those trends which affect the problem of coordination. While naturally there have been influences working favorably and others working unfavorably toward the problem it is clear that the preponderant effect of the development now being applied in the two industries is reducing the proportion of new situations in which specific coordinative measures are necessary. While to a considerable extent, as indicated in the body of the paper, this is due to the natural trends of plant design associated with new developments within each of the industries, it is also true that the extent of the progress made is due in no small measure to the careful study of all phases of the problem being conducted by the Joint Committee of the National Electric Light Association and the Bell Telephone System.

Under the guidance of this Committee and soon after its formation, the types of situations of physical proximity were classified and certain broad principles of cooperation were recommended. Soon thereafter more complete principles and detailed practises were formulated. These principles and practises were printed and widely distributed to companies and individuals directly interested in the problem of coordination.

The principles and practises thus set up were largely qualitative and the need for an organized program of research to establish quantitative data and to develop improved physical facilities for coordination was early recognized. Accordingly, the Joint Sub-committee on Development and Research was organized, and assigned the work of determining both experimentally and by field experience quantitative data covering the various aspects of coordination problems, and of developing detailed methods of effecting physical coordination. Under this Sub-committee a very large volume of research work has been undertaken. Results of some of this work have been published and a considerable amount is now in progress. The three papers to follow in the symposium discuss much more fully three of the most important aspects of coordination work at the present time and tell of the work being done in these fields by the Joint Sub-committee on Development and Research and by the other branches of the Joint General Committee's organization.

In reviewing this subject one is impressed by the number of ways in which the coordination problem touches both the telephone and power fields, and by the very large amount of cooperative work which has already been done. This work, as has been indicated, has resulted in great progress in the satisfactory handling of coordination matters of all types. This matter concerns two industries both of which are in a period of rapid development and change, both as regards their size and as regards the physical arrangements which constitute their plants. Many new developments in each plant require consideration from the standpoint of coordination. It is evident, therefore, that if the ground already gained is to be held and further progress made, the channels of cooperation between the two industries must be kept in operation both for the consideration of new problems arising with new developments in the industries, as well as for the further perfection of the cooperative methods of handling specific problems. These papers in other words do not constitute in any sense a final report. They are intended to show the present status of two very active and rapidly changing arts and to indicate the highly satisfactory results which have followed from a number of years of sincere cooperative effort between the telephone and power industries.

Status of Joint Development and Research on Noise Frequency Induction *

By H. L. WILLS and O. B. BLACKWELL

The work of finding out the technical facts bearing on the problems of the physical relations of power and telephone circuits was intrusted to the Joint Subcommittee on Development and Research of the National Electric Light Association and the Bell System. This paper has to do with this fact-finding work so far as it concerns noise frequency induction.

The work on inductive coordination may be classified into three groups of factors:

1. Influence factors which concern the characteristics of the power circuits.
2. Susceptiveness factors which concern the characteristics of the communication circuits.
3. Coupling factors which concern the interrelation of power and communication circuits.

The paper discusses these various factors in detail and describes the work done by the committee or in progress regarding them. References are given to published reports and papers which present the results of technical studies already completed.

Many of the existing noise frequency induction problems have arisen because of the development of the art of the two industries without such close cooperation between them as now exists. It is becoming evident, from the work of this Joint Subcommittee, that while it is not practicable to design machinery and apparatus for power systems to be entirely free of harmonics, or to ideally balance either power or telephone circuits, it is possible to control these factors within limits which, in conjunction with the control of coupling obtainable by cooperative planning of routes and coordination of transpositions, permit satisfactory operation of both services without unduly burdening either.

THE Joint Subcommittee on Development and Research is the agency through which the National Electric Light Association and the Bell Telephone System carry out technical work on problems of physical relations which vitally affect their respective growth and operating practises. In the present paper and companion papers the status of this joint development and research work is described.

The present paper, Part II of the Symposium, is concerned with problems of induction in telephone circuits under normal operating conditions of power systems which results in noise. Part III of the Symposium treats of induction at the power system fundamental frequency, principally that occurring at the time of grounds, short circuits or other abnormal conditions of power systems. Part IV of the Symposium treats of the physical relations and of the special noise-

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frequency and low-frequency problems brought about by the close proximity of the two types of service when occupying the same poles.

The Joint Subcommittee on Development and Research has subdivided its work among eleven project committees and assigned to each the actual carrying on of specific research work. Certain of the project committees are engaged on the problems described in this paper, while the remainder are concerned with the development and research problems of the companion papers, Parts III and IV of the Symposium. The names of these project committees, together with a statement of the phase of the problem considered by each, is given in Volume I of "Engineering Reports of the Joint Subcommittee on Development and Research." [1]

Naturally the first steps taken by the Joint Subcommittee were the review and appraisal of existing information and the exchange of data between the two interests represented. This paper includes a statement of the problem, with some review of the factors involved, the results accomplished by the subcommittee and the work projected in connection with each factor.

Classification of Factors Contributing to Induction

There are certain characteristics of a power circuit with its associated apparatus that determine the character and intensity of the electric or magnetic field which is set up in the surrounding medium. These characteristics are termed "Influence Factors." [2]

Likewise, there are certain characteristics of a communication circuit with its associated apparatus which determine its responsiveness to external electric or magnetic fields. These characteristics are termed its "Susceptiveness Factors." [2]

There is a third group of factors which refer to the interrelation of neighboring power and communication lines by electric or magnetic induction or both. These are termed "Coupling Factors." [2]

Inductive interference is thus the manifestation in the telephone circuit of a combination of influence, susceptiveness and coupling; and inductive coordination consists in the control of factors in all three of these classes to the degree required for satisfactory operation of both services.

Methods of Control

Physical Separation.—The first method which comes to mind for the control of inductive effects is that of physical separation obtained by placing the power and telephone lines on separate routes. A separation

[1] For references see bibliography.

between lines of a few hundred feet practically eliminates the noise-frequency problem whereas the low-frequency problem may exist with much greater separations. Since the same customers desire both communication and power services, the two kinds of distribution lines are necessarily often located on the same streets and highways. Power transmission lines and toll telephone lines do not, in general, have to be placed on particular routes and, therefore, separation can often be employed where such lines are involved. Cooperative advance planning on the part of the utilities in laying out their plants makes it possible to employ separation where it is readily feasible and economical.

Frequency Separation.—Another method of fundamental importance is the use of frequency separation. By this method, circuits to be coordinated are arranged so as to be responsive to different frequencies or bands of frequencies, and comparatively unresponsive to the frequency or band of frequencies employed for the other circuits. It is thus possible to make many different uses of electricity involving transmission in the same medium. This solution is familiar to us in the coordination of radio services.

Fig. 1 shows a diagram of the various uses of the frequency spectrum for electrical transmission and the manner in which power and communication services are coordinated by means of frequency selectivity.

The first commercial electrical energy available was in the form of direct current. Shortly thereafter, alternating current was used for the transmission of power. The nominal frequencies of the current used for this service in the earlier days range from 16⅔ cycles to 133 cycles. In American practise the frequencies used for power purposes have practically settled down to either 25 or 60 cycles. There is one extensive 50-cycle system and a few odd frequency systems. These latter of 30, 33, and 40 cycles, and perhaps others, are being rapidly eliminated, due to the importance of interconnecting them with 60-cycle systems. At the present time, there is some tendency for the use of higher frequencies in special machine shop applications. This use, at present, is principally at 180 cycles and need not concern us here as its extent is usually confined within a factory building.

In message telephone transmission, the prime consideration is the transmission of intelligible speech. While the range of response of the human ear is from about 16 cycles to 15,000 cycles per second, human speech occupies a narrower range and a still narrower band is adequate for intelligibility. The present voice-frequency telephone circuits, especially the longer ones, operate within a frequency band of about 250 to 2750 cycles per second. The frequency selectivity at the edges of the band is not sharp, however, so that extraneous currents at frequencies outside of this band may also give rise to noise. This is

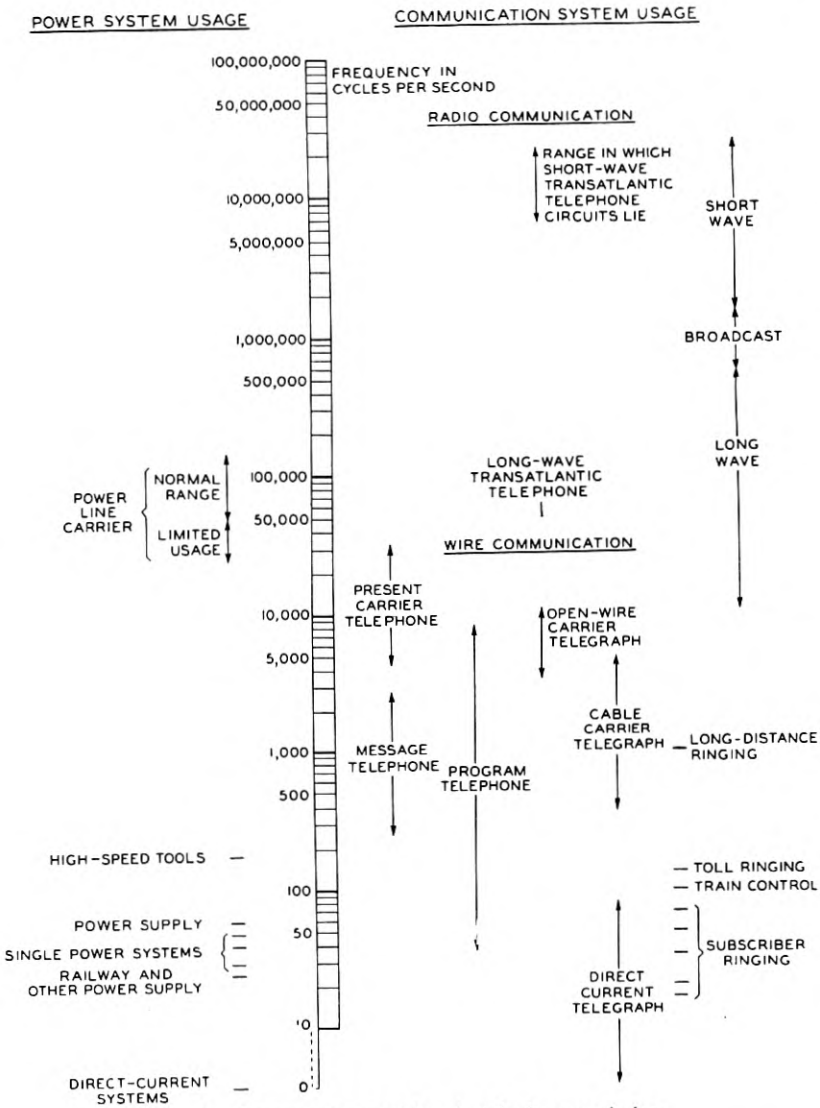

Fig. 1—Frequencies used for electrical transmission.

particularly true at the lower end with some of the local exchange circuits. High quality telephone circuits for program transmission cover a wider range. This may be on certain circuits as much as from about

35 to 8000 cycles per second, thus overlapping the fundamental frequencies used for power transmission.

Control of Power Levels.—Coordination by frequency separation becomes inadequate when the power levels of the various classes of services differ greatly as with power and telephone services. Thus, although incidental powers at harmonics of the power circuit fundamental frequency are negligible in comparison to the power at the fundamental frequency, they are large compared to the power employed in the telephone circuits and fall directly within the frequency range of the telephone circuits.

While the powers involved in telephone transmission are small as compared to those on power lines, they are in turn large as compared to the acoustical power received from the talker or delivered to the listener. The ordinary telephone transmitter is an amplifier, delivering to the line several hundred times the voice power which actuates the diaphram. On the other hand, the receiver requires an electrical power a hundred or more times that which it delivers as sound to the listener's ear.

It is obvious that the relative levels of harmonic-frequency power in the power circuits and voice-frequency power in the telephone circuits are of major importance in inductive coordination. These considerations have had large influence in the power field in the control of wave-shape of rotating machinery and transformers, and in the telephone field in fixing limitations on such factors as wire sizes, spacings of repeaters and instrument efficiencies.

Balance.—Among the most important methods of coordinating power and communication circuits is the control of their respective balances to ground and to each other. A power circuit with absolutely balanced voltages and currents impressed, and with the various conductors arranged in such a way that they would not establish external electric or magnetic fields, would not have any effect on any type of neighboring communication line.

Likewise, a telephone circuit in which there were no unbalances and in which the conductors were arranged in such a way that in the presence of an electric or magnetic field they would not have any voltages induced between them would not become noisy from any neighboring power circuits. Such an ideal state is impossible, but much has been accomplished by care in the design of the lines and equipment and by the transpositions of the conductors.

Shielding.—It is possible to materially reduce electric fields by interposing between disturbing and disturbed conductors grounded conductor surfaces known as shields. Magnetic fields can likewise be reduced by interposing conducting paths which circulate current to set up counter magnetic fields. The power and telephone cables in use are probably the simplest examples of shielding. A cable sheath is almost 100 per cent effective as a shield for electric induction, either on a power cable or on a telephone cable. The sheath is less effective as a shield for magnetic induction, because of its finite conductivity. It does not seem feasible at this time to obtain anywhere near perfect magnetic shielding.

Factors Contributing to Noise Frequency Induction

Influence Factors

There are two characteristics of a power system which are of primary importance in determining its inductive influence upon neighboring telephone systems, i.e., its wave-shape and its balance. The wave-shape is determined by characteristics of apparatus associated with the system. The balance is determined by the degree of symmetry of the supply voltages, load impedances, and of the series impedances and shunt admittances of the lines. While it is not practicable to design rotating machinery or other apparatus using magnetic cores entirely free from harmonics, or to realize ideally balanced three-phase systems, it is practicable to control both these factors within limits which, in conjunction with a similar degree of control on the coupling and in the susceptiveness of the communication circuits, permit satisfactory operation of both services without unduly burdening either.

The work on influence factors which has been conducted by the Joint Subcommittee on Development and Research has, therefore, been directed for the most part toward the study of the wave-shape characteristics of power systems and apparatus and methods for their improvement and the investigation of factors affecting the balance of the power systems and method for their control.

Wave Shape.—In initiating its work on influence factors, the Joint Subcommittee found little information available as to wave-shape which might be expected on operating power systems equipped with various types of apparatus. In order to obtain a broad picture of wave-shape conditions as they exist in the field, the Subcommittee conducted an extensive survey of wave-shape conditions on 34 operating power systems in the eastern half of the country. The program was arranged to obtain information as to the average and range of magnitudes of harmonics present in various types of transmission and distribution systems under normal operating conditions, to observe the relation between the wave shape of generating machinery under open-circuit conditions and under load, to study the effects of various transformer connections on wave shape, and to observe the effects on wave shape of various types and magnitudes of load.

The measurements made included analyses of the phase-to-neutral and phase-to-phase voltages and phase currents on a large number of generators, transmission lines and distribution feeders. Wherever practicable, data were obtained as to the balance of the operating systems by measurements of residual voltages and residual currents. Measurements were also made of the Telephone Interference Factors [3] of the voltages and currents. Where telephone circuit exposures suitable for test purposes existed, noise measurements were made on the communication lines to aid in determining the relation between power-system wave-shape and balance and telephone circuit noise. The actual measurements were for the most part conducted by the operating companies with the cooperation, during the first part of the testing program, of representatives of the Joint Subcommittee.

The mass of data accumulated during this survey is being summarized in several technical reports which it is anticipated will yield much valuable information pertaining to the wave-shape problem. An important practical application of these data will be in connection with the prediction of wave-shape conditions on new lines which are to be involved in exposures with communication systems and on which noise estimates are desired.

In general, the survey data indicate that the magnitudes of the harmonics present in voltage and current diminish with increasing frequency, with the exception that a pronounced dip occurs in the region from 800 to 1500 cycles. This is, no doubt, a result of the efforts of the machine designers to closely control the harmonics in this important region. Frequencies above 2000 cycles become extremely small except where these may be introduced on the power circuits by superposed carrier communication or signaling services. In general, the frequencies used for such services have been in the range from 50 to 200 kc., which is above the range employed for carrier communication on telephone lines.

In the general survey of wave-shape, no efforts were made to select feeders involved in cases of inductive interference. Aside from the survey work, however, representatives of the Subcommittee have participated in a number of investigations of such cases in which power-system wave-shape was an important factor. Much valuable data as to wave-shape conditions under which coordination difficulties are experienced have been obtained from these studies, while in obtaining these data the Subcommittee representatives have been of service to the local companies in the solution of the particular problems.

A limited amount of theoretical work has been carried on having to do with the effects of load on the harmonics observed in the open-circuit voltage of rotating machines. This work which was based on Blondel's two-reaction theory was supplemented by laboratory tests on several small machines. It was found that the reactions which take place within the rotating machines, particularly when two or more are operating in parallel, are so complicated as to practically preclude accurate computations of the effects. However, the data obtained from this investigation have been valuable in connection with later studies.

Balance.—A balanced power circuit is one in which the voltages between the various phase conductors and ground are equal in magnitude and sum up vectorially to zero and in which the phase currents are also equal in magnitude and sum up vectorially to zero. In a three-phase system where the currents or voltages are not equal but do sum up to zero, the currents or voltages can be resolved into two balanced three-phase systems, one of positive phase sequence and one of negative phase sequence. In cases where the currents or voltages do not sum up to zero they contain a single-phase component which is usually termed residual or zero-phase sequence component. Any three-phase system can be resolved into its balanced and residual components and each treated separately. The coupling for the residual components is usually much larger than for the balanced components and is therefore frequently of major importance in coordination problems. Differences in the magnitudes or departures from phase symmetry of the three impressed phase-to-neutral voltages, load or line unbalances, give rise to residual currents or voltages.

Experience has indicated that the outstanding factor in the unbalance of power systems is the existence of triple-harmonic voltages and currents which may arise either in rotating machinery or in transformers which are connected in star with grounded neutral. Since the triple-harmonic voltages in the three phase-to-neutral legs are in phase, they act in a path consisting of the phase conductors and an external return as, for instance, a metallic neutral or ground.

A large measure of control may be exercised on the magnitudes of the triple-harmonic residual voltages and currents by the use of certain transformer connections and by not operating the transformers at high flux densities.

The magnitudes of triple-harmonic residual currents in grounded-neutral systems may be minimized by the use of star-delta connected transformers, in which case nearly all the required triple-harmonic current circulates in the delta. The opposite extreme occurs with star-

star connections in which case the full triple-harmonic magnetizing current flows in the two systems which the transformer interconnects, the relative magnitudes in each depending on their relative impedances. Where a star-star bank is connected at one terminal of a line, with a star-delta at the other, the neutrals at each end being grounded, practically the entire third harmonic required by the star-star bank may be expected to circulate in the line connecting the two.

An effective method of control for cases in which star-star connections are required due to phase relations is the provision of a third set of windings or tertiaries in the transformers, the impedance of the tertiaries with respect to the other windings being sufficiently low to furnish an adequate path for the triple-harmonic magnetizing current. An alternate method of control, which also provides like phasing on the two sides of the bank, is the use of zig-zag connected transformers.

In four-wire multi-grounded neutral distribution systems, it has been found helpful in controlling the residual triple-harmonic currents from the single-phase load transformers to provide star-delta connected banks at various points in the network with neutrals connected to the system neutral. In some cases, these have been three-phase load banks, in others, special banks installed as a method of control.

The subcommittee is continuing its work on wave shape and balance through a laboratory study of transformer harmonics and transformer connections. These tests are being made on small model transformers, typical of the designs which are used for large sizes on transmission systems. It is planned to develop the theory applicable to harmonics from transformers on three-phase systems from the work on these laboratory models. It is planned to supplement the work by tests on large transformers in the manufacturer's shops and in the field.

A number of severe noise situations have been created during the past few years when star-connected generators, operating with grounded neutral,[4,5] have been connected directly or through star-star transformer banks to transmission or distribution systems. The interference in these cases resulted from triple-harmonic residual components impressed on the system by the particular generator operating with the grounded neutral. The magnitudes of these currents depend on the triple-harmonic components in the generator phase-to-neutral voltage and the impedance to ground of the system. The methods of control which have been successfully applied in these cases include the following:

1. Isolating the generator neutral and supplying the system ground through a suitably designed transformer bank.

2. Grounding the neutral of only those generators designed to be free from triple harmonics in their phase-to-neutral voltage.

3. The use of selective devices such as reactors or anti-resonant circuits commonly called "wave traps" in the generator neutral for suppressing the disturbing triple-harmonic components.

Non-triple harmonic residual voltages and currents may exist from differences of phase-to-neutral load impedances and from differences in the capacitances to ground of the three phase wires.

In multi-grounded neutral four-wire systems differences in the single-phase loads connected between the individual phases and the neutral may be important sources of residual current. A considerable measure of control may be exercised by restricting the size of single-phase areas and balancing the load on the different phases.

Capacitance unbalance to ground may be due to single-phase branches on three-phase distribution systems. Usually, the more important effect is that on the single-phase branch where the residual voltage is practically equal to the phase-to-neutral voltage. The unbalancing effect on the three-phase system may be minimized by equalizing the lengths of the branches connected to the several phases. The residual voltage on the single-phase branch can, where necessary, be eliminated by the use of isolating transformers or by converting to a three-phase branch.

Capacitance unbalance may also be due to dissymmetry in the arrangement of the wires of the circuit to each other and to ground. These unbalances are lowest in triangular configurations of the wires and largest when all the wires are in the same vertical or horizontal plane. With multi-circuit lines, a considerable measure of control may be obtained by suitable phase interconnection of the circuits. Transpositions are also effective in controlling these unbalances.

Coupling Factors.—The coupling between power and communication circuits is, of course, determined by the degree of their proximity, but it may be greatly modified by the balance of the two classes of circuits to each other and with respect to ground. While the most direct and certain method for reducing coupling is to avoid proximity, means are available for minimizing the coupling where necessary.

The work on coupling of the Joint Subcommittee on Development and Research, in the voice and carrier-frequency range, has been directed toward two objectives: (1) development of improved methods for predetermining the coupling to be expected in new cases of exposure, and (2) development of improved methods for reducing coupling for given degrees of proximity.

Several years ago the California Joint Committee on Inductive Interference [6] completed an extensive series of computations on coefficients of induction which were expressed in the form of curves for various physical relationships of power and telephone lines. These coefficients indicate the voltages induced in short, isolated, untransposed telephone circuits by unit voltage and current on similarly untransposed power circuits. They do not include the small separations involved with jointly used poles.

These curves and others based on them have been used for many years in determining relative coupling, when comparing different exposures, different routes involving various degrees of exposures, different configurations of power and telephone circuits and for other comparisons where all factors were substantially equal in the situations being compared, except those involved in determining the coefficient of induction. For these purposes they have been very useful. Methods have not, however, been available whereby these coefficients could be used for computing noise where transposed circuits were involved and where many telephone wires were on the line, which exert an important shielding effect on each other.

The Joint Subcommittee on Development and Research has been conducting experimental studies both for highway and wider separations, and those occurring with jointly used poles, so that the effects of transpositions and of mutual shielding of the many wires involved might be properly taken into account in determining the noise currents in the metallic circuits.

In determining the coupling between power and telephone circuits, it is desirable to differentiate between the effects of the balanced and residual components of the voltages or currents of the power circuit, between the effects of voltages and those of currents, and on the telephone line between induced voltage which acts directly in the metallic circuit, termed "metallic-circuit induction," and that which acts in the circuit composed of the wires with ground return, termed "longitudinal-circuit induction."

Since the residual components act in a circuit having ground as one side with the wires in parallel for the other, while the balanced components are confined to the wires of the system, the coupling for the residual components is much greater than for the balanced components. The coupling for the balanced components may be reduced by the use of power-circuit transpositions, while such transpositions have no effect on coupling for the residual components.

The distance between the power and telephone wires is usually large as compared to the spacing of the wires of the telephone circuit, so that the longitudinal induced voltages are large as compared to the metallic-circuit voltages. The effect of the telephone transpositions being merely to equalize the relations of the two sides of the telephone circuit to the power circuit, such transpositions do not change the magnitude of the longitudinal voltages, but do reduce the metallic-circuit voltages.

The relative magnitudes of inducing voltages and currents differ widely among various power circuits, and may vary greatly with time on any given circuit. They will also differ considerably at a given time and on a given circuit among the various frequencies involved. For this reason it is necessary to consider separately the coupling arising through the electric and magnetic fields.

Voltages induced in metallic circuits for the separations between lines usually encountered are practically proportional to the spacing of the wires of the telephone circuit. Voltages induced in eight-inch spaced pairs are thus approximately two-thirds of those induced in 12-inch pairs, while those induced in phantoms on 12-inch spaced side circuits are twice those induced in the sides. The longitudinal voltages are, however, practically independent of the wire spacing so that the contributions which these voltages make to noise in the metallic circuit are unchanged except as the change in spacing may affect the balance to ground.

Spacing of the wires on the power circuit and their configuration also have an important effect on the coupling for the balanced voltages and currents, the coupling, in general, increasing as the spacing increases. Coupling for the residual components is, however, affected only to a minor degree by the spacing and configuration. Much information bearing on these matters is included in the material on coefficients of induction published by the California Commission referred to above.

Measurements of coupling have been made by the subcommittee in a number of situations. These have included cases of (1) exposure of overhead transmission lines and open-wire toll telephone circuits at highway separations, (2) overhead distribution lines and subscribers' telephone cables in joint use and at street separations and (3) overhead distribution lines and subscribers' open-wire circuits in joint use. Information was obtained on coupling both for voltages and currents and for the balanced and residual components. The results of the work on overhead distribution lines and subscribers' telephone cables have already been published.[7] The other data are to be published as soon as they are prepared in suitable form.

The work on overhead distribution lines and subscribers' circuits is relatively complete, covering a wide range of conditions typical of those encountered in the field. Various arrangements of primary and secondary conductors covering single-phase and three-phase, three-wire and three-phase, four-wire systems were investigated. The shielding effect of the telephone cable was determined and, with the open-wire subscribers' telephone circuits, the shielding effect of the various telephone wires on each other.

For telephone cable circuits when the sheath is grounded at either one or both ends, the inductive effect of the power circuit voltages on the wires enclosed is negligible as compared to that of the power circuit currents. Furthermore, because of the close association of the wires of a pair in the cable and the frequent twist, the metallic-circuit induced voltages are negligibly small as compared to the longitudinal voltages so that, in general, only the magnetic longitudinal coupling factors are of importance in these situations.

The work further indicates that, for most practical problems involving overhead distribution lines of the multi-grounded type and subscribers' cable circuits, a knowledge of the coupling for the residual or unbalanced currents is sufficient, the effect of the balanced currents being relatively unimportant. However, in cases where the line currents are particularly heavy or contain exceptionally large harmonic components, the balanced currents become important.

In the range of frequencies used for telephone transmission the ratio of open-circuit voltage induced on a telephone line through electric induction to inducing voltage on the power circuit is substantially independent of frequency. When the exposed section of line is connected to the remaining section of the telephone line or to terminal apparatus, a current is set up which is approximately proportional to the frequency of the induced voltage. The circuit will perform as if there were a small condenser connected between the power circuit and telephone circuit and the induced current experienced will be proportional to the frequency and the magnitude of the inducing voltage on the power circuit.

The coupling between power and telephone circuits for currents is in the nature of a mutual inductance, so that the voltage induced in the telephone circuit is proportional to the magnitude of the inducing current in the power circuit and its frequency.

This statement applies strictly only to induction from the balanced current components. Induction from residual current in the power circuit is complicated by the effect of the finite conductivity of the earth. With increasing frequency the earth currents tend to be closer to the surface and the coupling with the telephone circuit tends to increase less rapidly than would follow from proportionality with frequency. The departure from linearity is not large in the frequency range from 250–2750 for highway separations and for joint use.

Transpositions afford one of the most powerful means available for controlling coupling of power and open-wire telephone circuits in given situations of proximity. Transpositions operate by neutralizing, in one section, inductive effects which arise in a closely adjacent section. It is evident that, in order for transpositions to be fully effective, conditions must be substantially alike among the various sections to be neutralized as regards relations of the power and telephone circuits to each other, to ground, and among the various circuits on each line. This latter condition more often applies to the telephone lines, as they usually comprise many circuits.

These conditions require that balanced and coordinated systems of transpositions be provided between each point of discontinuity in the exposure. By "discontinuity" is meant any point at which an important change takes place in the physical or electrical conditions of the circuits, such as loads, branch circuits, series impedances, etc.; any change in configuration, in the separation of the two classes of circuit or in their position relative to ground or to some other circuits which may be associated with either power or telephone circuits closely enough to appreciably modify the induction.

In addition to meeting these conditions, the telephone transpositions must also satisfy the requirements for minimizing cross talk among the various telephone circuits. This, in general, requires telephone transposition arrangements of considerable complexity. For this purpose standard transposition arrangements are available,[8] adapted for different lengths depending upon the distances between the successive discontinuities.

In most cases unavoidable irregularities occur in the spacing of poles, in distances between power and telephone circuits, in presence of shielding objects, such as trees, and in height of poles, which it is not possible to treat as discontinuities and take into account in the transposition design. In cases where these irregularities are large, the effectiveness of the transposition arrangements is greatly impaired. The extent to which the effectiveness of such arrangements is imparied due to these non-uniform conditions is a problem not easily susceptible to mathematical analysis and reliable information is not now available. The subcommittee is planning to investigate this problem experimentally by tests on a number of situations involving operating circuits.

Susceptiveness Factors.—The degree to which telephone transmission is adversely affected by noise-frequency induction depends not only upon the magnitudes of the induced voltages as determined by influence and coupling factors, but also upon the susceptiveness factors of the telephone system. These include the manner in which the induced voltages and currents are propagated to the circuit terminals together with the reactions of the circuit unbalances, thus relating the current in the terminal apparatus to the induced voltages, the sensitivity of the receiving apparatus and the operating power level of the telephone circuits.

Propagation Effects and Balance.—Important differences exist with respect to propagation effects and balance between open-wire and cable circuits and between toll and exchange systems.

As pointed out in the discussion of coupling, only the magnetically induced longitudinal voltages and currents affect telephone cable circuits. Because of the absence of electric induction and direct metallic-circuit induction and because of the important shielding effects exerted by the cable sheath and the various telephone circuits on each other, telephone cable circuits are much less susceptive than open-wire circuits.

In open-wire telephone systems consideration must be given both to electric and magnetic induction and to voltages directly induced in the metallic circuit as well as to those induced in the longitudinal circuit. In a line composed of a number of circuits, the currents set up in any one circuit depend, not only upon the voltage induced in that circuit and its impedance, but also upon the currents and voltages which are set up in the rest of the telephone circuits on the line. It is not possible, therefore, to calculate the induced currents merely from a knowledge of the magnitudes of the currents and voltages on the power circuits and the coupling between the power circuits and isolated pairs of wires on the telephone line, considered independently.

These mutual effects among the various telephone circuits exist both within and without the exposed sections. Thus, the propagation of the induced voltages and currents along any one circuit is influenced both by the electrical conditions of this circuit and also by the conditions of all other wires on the line. Additional complexities arise in the propagation of the induced voltages and currents, because of non-uniformity in impedances to ground at terminals, points where circuits join or leave the line, and where lengths of cable may be used at terminals or at intermediate points. The impedances to longitudinal induced voltages and currents vary over a wide range depending on the number of wires on the line, the relative position of the exposure and the circuit terminals and the occurrence of sections of cable. Due to reflection effects from these irregularities, peaks of current and voltage may exist along the circuits which are large as compared to the corresponding magnitudes at the exposure terminals. If circuit unbalances happen to exits at these maximum points, metallic-circuit voltages and currents thereby introduced are increased.

While the distribution of longitudinal voltages and currents among the various wires upon the telephone line depends upon the nature of the inducing field in which it is placed, the experiments of the committee have shown that a satisfactory degree of approximation for studying propagation effects can be obtained by energizing all wires on the line simultaneously at the same potential from a common source. An extensive experimental study has been made in this way by the committee in which the magnitudes of the longitudinal voltages and currents at various points along the line have been measured as well as metallic-circuit currents set up through the unbalances at the sending and receiving ends of the line.

By making measurements of this sort on a considerable number of lines of different types of construction and different transposition arrangements, it is hoped to obtain statistical data whereby the metallic-circuit voltages and currents at the circuit terminals may be determined from the magnitudes of longitudinal voltages and currents as measured at exposure terminals.

Unbalances in toll circuits are the result of commercial variation from the balanced condition, since the circuits are designed to be symmetrical. These unbalances may consist of resistances in joints, capacitance or inductance unbalances due to irregularities in transposition spacing or to omitted or unspecified transpositions, or differences in the impedances of apparatus connected in series with the wires or between them and ground. These unbalances are fortuitous both as regards their magnitudes and location along the toll circuits. Some increase in importance with frequency and others decrease. These, combined with the irregularities in the propagation of the longitudinal voltages and currents, cause the resulting metallic-circuit currents in individual circuits to vary in an erratic fashion with frequency. The general trend is one of proportionality, independent of frequency within the important range, between the longitudinal currents and voltages at the exposure and current in the metallic circuit at the terminals. Taking into consideration the effects on coupling, the currents at the terminals increase approximately in direct proportion to the frequency of the inducing voltage or current on the power circuits.

Because of the lower susceptiveness of cable circuits together with the high degree of balance of the terminal apparatus and because of the more general use of private rights-of-way, cases of noise-frequency induction into toll cable circuits have been comparatively infrequent. For this reason the attention of the subcommittee as far as toll systems are concerned, has been directed toward open-wire circuits.

In exchange circuits certain inherent unbalances exist due to the arrangements employed for supervisory signaling, for selective ringing, and for coin box service. The supervisory system utilizes a low impedance relay connected in series with one side of the central office interconnecting circuit. The selective ringing scheme involves connecting the ringer windings from one side of the line to ground at the station set. For the coin box service, a coin-collect relay winding is connected between one side of the station set and ground. These unbalances have been investigated in detail by the committee and the results have been published [7] as described later.

The unbalance of party lines due to the ringer ground is usually much more important than that of the central office interconnecting circuit due to the supervisory relay. Both are, in general, more important than the cable unbalances. Coordination difficulties between telephone exchange systems and power distribution systems thus usually involve the party-line circuits before the individual-line circuits are affected.

The controlling unbalance in the exchange plant when in cable being in the nature of an inductance between one side of the line and ground, its importance decreases with increasing frequency of the induced longitudinal voltage. This effect largely counter-balances the increase in coupling with frequency. Thus, in most situations involving joint use of poles by distribution circuits and exchange cable telephone circuits, induced currents of the third and fifth harmonics of the power circuit fundamental frequency assume chief importance.

Exceptions are cases where outstanding harmonics in the range between 800 and 1500 cycles are present on the power circuits. In these cases, particularly where the exposures are long, the central office apparatus unbalances may be more important than those of the party-line station apparatus.

The method which has been found most generally applicable for reducing the susceptiveness of exchange cable circuits is the grounding of the cable sheaths. This reduces through shielding the magnitudes of the longitudinal voltages and currents. Special station sets having lower susceptiveness have been used in specific cases where their use appeared to be the best method.

Power Level and Sensitivity. The magnitudes of the induced currents in the telephone system having been determined by the influence factors, the coupling, and the unbalances of the telephone circuits, the degree to which they impair telephone service depends upon their intensity as compared to the intensity of the telephone currents.

Consideration has been given by the subcommittee to the possibility of increases in power levels (a) on local exchange circuits and (b) on toll circuits. Little promise has been found in the proposal to raise voice power levels in the local exchange plant as a means of reducing the effects of noise. As previously pointed out, present telephone transmitters materially amplify the power received from the voice so that the electrical power on the telephone line is some hundreds of times greater than the acoustic power applied. In development work on telephone transmitters, telephone engineers are proceeding on the basis that more is to be gained by improving the frequency response of the transmitter than can be gained by mere increase of power. This line of development has, of course, the effect of raising power levels at frequencies where they have been relatively low.

Two proposals for application to the toll telephone plant were studied. One would involve changing the repeaters now in use at terminals and at intermediate points to a more powerful type and equipping all toll circuits with terminal repeaters of this same type. This would permit raising the power levels without altering the relative levels of the various telephone circuits and thus would not change the crosstalk. Another would involve such changes only on certain long toll circuits, leaving the remainder of the circuits at their present levels. As the result of a trial installation, it was found that to realize any appreciable change in level on these circuits, very extensive changes would be required to avoid crosstalk from the higher level circuits to the remaining ones which were not changed.

The levels employed in carrier telephone circuits, while somewhat lower than those used on voice-frequency open-wire telephone circuits at the receiving end, are higher at the sending ends than the corresponding voice-frequency levels. Since the power system harmonics in the carrier-frequency range normally are small as compared to those in the voice-frequency range, carrier-frequency open-wire systems experience considerably less noise from power systems.

Effects of Noise.—The actual voice power level on telephone circuits varies over a wide range, depending upon the particular user, his distance from the telephone central office, and by the transmission loss in the connection between the two subscribers. Impairment caused by a given amount of line noise on the circuit may also vary over a considerable range, depending upon the voice power level and the noise in the room where the telephone is being used. The method in use by the Bell System for an engineering basis in considering the effects of noise on telephone conversation is to substitute for the noise increases in the transmission loss of the circuit. Thus, the circuit with its actual loss and noise is represented by a circuit of lower noise and increased transmission loss. These added losses are known as Noise Transmission Impairments and are abbreviated N. T. I. The N. T. I.'s were determined from articulation tests and judgment tests made on noisy and quiet circuits, and were set up on the basis of typical talker volumes, transmission equivalents, and amounts of room noise at the station terminals. Additional transmission loss was added to the quiet circuits so that noisy and quiet circuits gave equal articulation or were judged by the observers to be equivalent in their transmission performance. Thus, the N. T. I.'s are used to indicate an additional transmission loss or impairment which is occasioned by the presence of the noise.

The articulation and other tests on which these N. T. I. ratings were based are now being supplemented by tests conducted under the direction of the subcommittee. Measurements are being made of the effects of various magnitudes and sorts of line noise in the presence of typical amounts of room noise, as determined from a room noise survey made by the subcommittee, and for representative toll connections and talker volumes. The line noises being employed are those found typical from an extensive survey made by the subcommittee on open-wire toll circuits throughout the country. These tests will afford a basis for comparing various methods of measuring line noise, including ear comparison methods now in general use and new visual meter methods now under development. Thus, this work should lead to a mutually acceptable method for measuring noise and a basis upon which agreement may be reached as to the impairment in telephone transmission caused by noise.

Published Results.—As various phases of the technical work being done are completed, they are published in the form of Engineering Reports which are released by the Engineering Subcommittee of National Electric Light Association and Bell Telephone System. Eight reports, of which five refer to matters concerning noise-frequency induction, have already been issued. Other reports dealing with this subject have been recently approved by the Engineering Subcommittee and will soon be issued. Certain other technical results which have come from the Subcommittee's work have been presented by various individuals connected with the work in papers before the A. I. E. E. Still other results have been published in brief articles in the N. E. L. A. *Bulletin*.

One of the problems upon which the technical work of the committee has been completed and published is that of inductive coordination of primary distribution systems and exchange telephone circuits in cable. The results of this work are given in detail in a report [7] entitled "Minneapolis Joint Use Investigation." This report includes information on influence factors applying to various types of power distribution systems, including three-phase, three-wire and three-phase, four-wire systems with various arrangements of neutral grounding, data on coupling between various typical arrangements of these systems and telephone cable circuits, and information on susceptiveness characteristics of telephone systems, including unbalances of lines and apparatus. To facilitate the use of this information in the day-by-day coordination problems handled by the operating companies, a summarizing report [9] entitled "Short-Cut Methods for Calculating Noise in Local Telephone Subscribers' Circuits in Cable Due to Exposures to Power Distribution Circuits" has been prepared. This report presents empirical formulas for estimating noise-frequency induction and includes a brief discussion of the technical factors involved and the approximations underlying the formulas. Means are described for reducing influence by the control of triple-harmonic exciting currents and load unbalances of power distribution circuits, and for reducing susceptiveness by grounding telephone cable sheaths and by controlling the unbalances of the telephone station equipment. The information should be useful to engineers of the operating companies in the cooperative planning of routes to avoid induction troubles.

While a large part of the experimental work connected with the problem of joint use of local open-wire subscribers' circuits and power distribution circuits has been completed, the detailed technical reports have not yet been completed for publication. However, a summarizing report [10] which it is believed will largely fill the needs of the engineers of operating power and telephone companies has been completed. This is entitled "Short-Cut Methods for Calculating Noise in Open-Wire Subscribers' Circuits Due to Joint Use Exposures to Power Distribution Circuits."

Three reports have been issued dealing with the problem of coordination of open-wire toll circuits and overhead transmission and distribution lines. The first [11] discusses the "Termination of Isolated Exposure Sections to Obtain Normal Metallic-Circuit Currents," which affords a means of taking into account the shielding effects present when the line is in normal operating condition. The second report [12] describes "A Method of Measuring the Balance of Open-Wire Telephone Circuits with Respect to Longitudinal-Circuit Induction," which should be useful to the field in the making of special tests and in supplying statistical data of value for estimating noise effects on open-wire line circuits. The third report,[13] dealing with "Methods of Measuring Noise on Open-Wire Toll Circuits," is a detailed presentation of the various types of tests for studying noise problems on toll lines, and includes a discussion of the method of analyzing the test data.

Another report [5] deals with "The Effects on Inductive Coordination of Generators Feeding Directly on the Line and Operating with

Grounded Neutrals." This report includes a detailed discussion of the factors involved and describes methods which have been developed for control of the triple-harmonic residual currents and voltages which occur with this method of operation.

The results of the work done by the subcommittee on a survey of room noise in telephone locations were described in a recent paper.[14] While this was an incidental phase of the general study on effects of noise on telephone transmission, it was felt to be of timely value, particularly in respect to the methods of measurement employed. Using the results of the data obtained in surveys of wave shape on operating power systems and analyses of noise current on telephone circuits, a paper [15] was prepared on the frequency response characteristics of telephone transmitters and receivers. This paper indicated that there appeared to be no advantage, in reducing effects of noise, in shifting the resonance points of telephone transmitters and receivers from their present region, as the frequency distribution of the noise currents was such as to give a minimum in this resonance region.

At the time that the joint work was started the need arose for considerable special apparatus to make the measurements which were required. Some of the important pieces of apparatus for the work in the voice-frequency range were sensitive single-frequency voltmeters and ammeters. These needs were taken care of by the development of sensitive analyzers whereby single-frequency voltages or currents could be selected from complex wave shapes on either power or telephone circuits. One form of this apparatus has been described in a paper before the Institute [16] and another in a serial report [17] of the National Electric Light Association.

In connection with the survey of room noise, a room noise meter was developed. This was described in the paper [14] previously referred to which presented the results of this survey.

Further Work of the Subcommittee

When the subcommittee started its work there was before it an accumulation of technical problems which had arisen as the arts developed without such close cooperation as now exists. The statements given above regarding various phases of the subcommittee's work on noise-frequency induction indicate the substantial progress which has been made in the solution of these accumulated problems. They convey also a general picture of the work which the subcommittee has immediately before it.

It must not be thought, however, that when these accumulated problems have been solved the work of the subcommittee will be completed and its efforts discontinued. This cooperative work must always bear a relation to the total development efforts of both the power and communication fields. As has already been pointed out, this work is concerned with two electrical arts which have been particularly noteworthy for their success in constantly developing their technical methods and expanding their services. These developments will surely continue and constant consideration of the physical problems of coordination is needed to insure that such developments act to steadily improve rather than to make more difficult the coordination of power and communication circuits.

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Status of Joint Development and Research on Low-Frequency Induction *

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This paper deals with coordination of power and telephone systems with respect to induction at power system frequency, usually 60 cycles. The principal problem in this field relates to effects produced under abnormal conditions on power systems. The factors controlling the magnitude, frequency of occurrence, duration, and effects, of induced voltages, are discussed. Different types of protective measures, some applicable to power systems and others to communication systems, are outlined, including their respective advantages, limitations, and fields of application. The reaction on this problem of lightning and of situations involving liability of contacts between telephone wires and power wires is touched upon. The whole matter is treated from the standpoint of the comprehensive joint investigation of the interference problem which is being conducted by the N.E.L.A. and the Bell System.

INDUCTION at power system fundamental frequency, commonly called "low-frequency" induction, has different characteristics and produces quite different effects from induction at the noise frequencies discussed in the paper by Messrs. Blackwell and Wills. Since very little has been published on low-frequency induction, it seems desirable, in order to make clear what the Joint Subcommittee on Development and Research is doing on this subject, to explain the problem in some detail.

The disturbances in communication circuits due to low-frequency induction are in general discrete occurrences, coincident with accidental grounds or other faults on neighboring power lines, rather than being continuous and due to normal power line operation.

Three-phase power circuits, when operating normally, are so nearly balanced with respect to earth at their fundamental frequency, and telephone circuits of the ordinary type are relatively so insensitive at frequencies of 60 or 25 cycles, that induction at these low frequencies under normal power line conditions is rarely a practical problem. But when abnormal conditions, particularly faults to ground, occur on power lines, large unbalanced voltages and currents at fundamental frequency exist temporarily and at such times there may be induced in neighboring telephone circuits voltages which are hundreds of times as great as under normal operating conditions. The induced voltages under abnormal conditions may reach values sufficient to cause hazard

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to telephone employees or interruption to service. Although such abnormal conditions occur infrequently and usually last for only the very short period required to interrupt or clear the power circuit, the effects which may be produced are so serious that protection against this type of induction is an outstanding problem in the coordination of power and telephone systems. A large part of the subcommittee's work has for its object the development of means for controlling and minimizing such induced voltages and their effects.

While low-frequency induction is not usually severe except under abnormal conditions, power circuits which operate at any time on an unbalanced basis, or which are closely coupled to grounded wires capable of carrying large currents may, even under normal operating conditions, create a problem of low-frequency induction in paralleling telephone circuits in addition to setting up high-frequency disturbances as explained in the Blackwell-Wills paper. This is particularly true where the exposed telephone circuits are used for special services such as the transmission of radio broadcasting programs. Grounded types of telegraph and other signal circuits also are sensitive to low-frequency induction.

Classification of Factors Responsible for Inductive Effects

The same three class of factors which combine to underlie the noise-frequency problem appear also in the low-frequency problem. As they appear in the latter, these are:

1. "Influence factors" in the power system, which are concerned with the magnitude, duration, and frequency of occurrence, of unbalanced voltages and currents.

2. "Susceptiveness factors" in the communication system, which are concerned with the nature and seriousness of the effects produced by the induced voltages.

3. "Coupling factors" which determine the magnitude of the voltages induced in the communication system, per unit unbalanced voltage or current of the power system.

In the low-frequency induction problem, the coupling factors are largely dependent upon the characteristics of the earth and the relations of power and telephone systems to the earth. If the earth were an insulator instead of a conductor there could, of course, be no such thing as fault current in the earth and the coupling between power and communication circuits would be much less. It would not then be hazardous for a lineman when in contact with earth to touch a charged wire. Or if the lines were not in proximity to the earth, there would be no chance for a lineman working on the wires to get in contact with earth. Neither in power systems nor in telephone systems is it actually necessary that the earth be used as part of an operating circuit but, as the earth is a conductor, and power and telephone lines and apparatus are located on its surface, it is essential in both systems that the earth be taken into account in circuit problems and that paths to earth for protective purposes be established at certain points.

It must not be assumed, however, that the earth is a perfect conductor. For the most part the materials of which the earth's crust is composed are of relatively low conductivity. From numerous measurements in various places the average conductivity over considerable volumes of earth has been found to range from 10^{-11} to 10^{-15} abmho per cm. cube. The resistance of an earth path is therefore not zero but may be many ohms or even in some cases many hundreds of ohms. Most of this resistance is in the immediate vicinity of the electrodes and can be reduced by increasing the surface area of contact between electrode and ground.

In discussing the low-frequency induction problem, it is convenient to consider the factors controlling:

(1) The magnitude of induced voltages, (2) the frequency of occurrence of induced voltages, (3) the duration of induced voltages, and (4) the effects produced by induced voltages.

Factors Controlling the Magnitude of Induced Voltages

The magnitude of voltages induced in telephone systems in specific cases depends chiefly on the magnitude of residual currents and voltages resulting from power circuit faults to ground and on the exposure conditions.

Residual Currents and Voltages. A balanced power circuit is one in which the voltages from the various phase conductors to ground are equal and sum up vectorially to zero and in which the phase currents also are equal and sum up to zero. Under this condition all the currents in the circuit are *balanced* currents and all the voltages are *balanced* voltages. If, however, one phase develops a fault to ground, this relation becomes disturbed, the voltages to ground of the phases become unequal, and their vector sum, which is the *residual* voltage (3 times the so-called uniphase or zero phase sequence voltage) of the power circuit, is no longer zero. The currents in the three phases likewise become unequal and when added vectorially their sum, which is the *residual* current (uniphase or zero phase sequence current) of the power circuit, is no longer zero. In most low-frequency induction problems residual current is far more important than residual voltage.

Residual voltages and currents are equivalent to single-phase voltages and currents applied to a circuit consisting of the three line conductors in parallel as one side, and the earth as the other side. Their large inductive effects are due to the great dimension of the loop formed by this earth return circuit, much of the return current being effectively so deep in the earth that its neutralizing action is small. In the case of the balanced components, the inductive effect due to the voltage or current of one conductor is largely neutralized by the voltages or currents of the other two conductors.

The chief characteristics which determine the magnitude of the residual voltages and currents are (1) the power circuit voltage, (2) the impedances of the neutral ground connections, (3) the line and apparatus impedances, (4) the fault and earth impedances, (5) the sources of power supply, (6) the character of ground wires if used, and (7) the circuit configuration including ground wires.

When a fault occurs between a phase conductor and earth on a power system having neutral ground connections, these neutral connections, together with the fault, line conductors and earth, form a closed circuit for the residual current. Unless the neutral impedance is very high, e.g., approaching that of an isolated system, the shunting effect of the capacitance to ground of the line conductors may for most purposes be neglected and practically the same value of residual current exists at all points along the line between the fault and the neutral connection to ground. For simplicity, a system with a single line and single neutral ground connection may be assumed. With this picture in mind, it is clear that the value of the neutral impedance may be an important factor in determining the magnitude of the residual current. If the fault occurs near the point where the neutral is grounded, the line and apparatus impedances being low, a small impedance in the neutral may control the current. On the other hand, for faults occurring at points remote from where the neutral is grounded, the impedance in the neutral connection may have to be relatively large to materially reduce the residual current.

As one limit there is the solidly grounded neutral, i.e., no impedance is inserted and as good a ground as practicable obtained. This obviously permits maximum residual current when ground faults occur. Unless the grounding impedance is very high the residual current, and not the residual voltage, is the controlling factor in grounded neutral systems.

As the other limit there is the isolated neutral, i.e., the impedance from neutral to earth is infinite. In this case no residual current passes through the neutral. At the ends of the line the residual current is zero, gradually increasing to a maximum at the point of fault. The circuit for residuals is through the capacitance of the line to ground, the magnitude of this capacitance controlling the magnitude of the residual current, which is much less than with grounded neutral systems except in cases of double faults when it may be very large. With a single fault the residual voltage may be a more important factor in respect to induction than residual current.

The impedance of the fault itself depends upon a number of things, including the type of line construction and the earth conditions. The subcommittee has under way investigations to gather data on the range of fault impedances under different conditions. To determine the maximum residual current, the fault impedance may be taken as zero. In many instances, this approximation gives sufficiently close results, particularly if the fault is remote from the grounded neutral so that line, neutral and apparatus impedances are controlling. In case of conductors falling upon the ground, local earth conditions largely determine the fault impedance. On a steel tower line an insulator breakdown results in a relatively short arcing path to grounded metal, whereas, in wood pole construction, the pole itself introduces considerable impedance unless nullified by guys or other metal.

The foregoing discussion of residual current has been confined practically to the situation brought about by single faults to ground. Double faults at separate locations sometimes occur and these are equivalent to a phase-to-phase short circuit through the earth, giving a large residual current in the intervening section of line. If the two faults in such a case are on opposite sides of an exposure, very severe induction may result. Experience shows that double faults at separate locations constitute only a few per cent of the total faults occurring on grounded-neutral power systems but are a much larger percentage of the total faults on systems normally isolated from ground.

The presence of ground wires on a line may have considerable influence on fault impedance. Being connected to ground at frequent intervals, such wires decrease the impedance to ground where a breakdown occurs between a phase conductor and a ground wire or any metal in contact with a ground wire. A ground wire tends to increase the total residual current but on the other hand its controlling function, from the induction standpoint, is that of a shielding conductor tending to decrease the induced voltage.

Circuit configuration does not have a large influence on unbalances due to abnormal conditions, but it has an important effect upon any unbalance of a power circuit under normal operating conditions. To be balanced, the phases of the power circuit must be symmetrical with respect to each other and to earth. To the extent that the capacitances and inductances of the several phase conductors differ, residual voltages and currents will result. Transpositions afford a means for compensating for these circuit unbalances.

In cases for which protective measures are being considered, it is important to be able to estimate the magnitude of the residual current when faults occur at different points on the power system. Apart from inductive effects, this is a question of importance to power companies, since forecast of currents under different fault conditions is essential in the design and setting of protective relays. Much work has therefore been done by different investigators on methods of predetermining these currents. Helpful mathematical methods have been developed, though sometimes the results obtained by their use are open to question due to lack of accurate values of some of the important impedances. Proper allowance for fault impedance and the effect of ground wires is sometimes difficult to determine and in cases of complicated networks approximations usually have to be made. To facilitate the numerical computations, calculating boards of varying degrees of elaborateness have been developed. The subcommittee is investigating this matter and by experimental work is checking the results of estimates and acquiring further knowledge of the range of the variable factors. Through this work, it is hoped to increase the convenience and accuracy of these important computations.

Exposure Conditions.—The relationship between power and telephone lines with respect to the exposure conditions is defined by the "coupling coefficient" or "coefficient of induction," a factor which, when multiplied by the value of current (or voltage) in the power line, gives the resulting voltage set up in the telephone line. A power line and a neighboring telephone line have several different coupling coefficients corresponding to different conditions, such as, whether the induced voltages are due to power current or power voltage, to balanced or residual components, and whether they are voltages induced along the conductors (or to ground) or are induced directly in the metallic circuit. Low-frequency induction is predominantly magnetic in character and the coupling which is most significant is that between the power conductors and the telephone conductors, both considered with earth return. The induced voltages are due principally to "longitudinal circuit induction."

A number of dimensional factors affect the magnitude of this coupling, such as the length of the exposure, the separation between lines, and the locations of ground connections on the two systems. Local conditions as to earth conductivity and the arrangement of geological strata for some distance below the earth's surface, constitute other important factors. An accurate mathematical evaluation of the coupling between earth return circuits is difficult. Formulas have been developed under simplifying assumptions as to symmetry and homogeneity, which aid in explaining and interpreting experimental results and in predicting approximate values of coupling in cases where experimental measurements are not available.

Assuming uniformity of exposure conditions the coupling varies directly with length of parallelism, except for end effects or interactions between ground connections of the two lines. Increase in separation of the lines diminishes the coupling but the exact relationship depends upon the distribution of current in the earth which in turn depends upon the frequency and the earth conductivity. In many cases different strata of different conductivities are involved in the path of the earth current, which adds to the difficulty of correlating experimental and theoretical results. The effect of earth conductivity on coupling is accentuated as the lines are more widely separated. At roadway separation, large differences in earth conductivity affect the coupling only moderately; but at separations of one half mile to one mile, coupling values may differ by 20 to 1 or more, due to the range in value of earth conductivity. Irregularities in exposure conditions such as changes in direction of one or both lines, crossovers, and angular exposures of varying separation, are complications which frequently occur in practise.

The voltages set up in neighboring communication circuits by power currents are due usually to inductive coupling but in some cases are due partly or wholly to resistive coupling. It is seldom necessary in practical studies to try to segregate these two components of voltage, since their effects in the telephone system are not a function of the phase relationships of these components to the power line current which produces them. It is not unusual to speak of inductive coupling as including both inductive and resistive coupling.

Any grounded circuit in proximity to power and telephone lines within an exposure brings about a certain amount of shielding through the reaction of the currents induced in this conductor upon the primary magnetic field set up by the residual current in the power circuit. In this respect a shield wire acts like a short-circuited turn on a transformer. The effectiveness of the shielding depends upon the conductance of the shield wire, the manner and effectiveness of its grounding, and its position with respect to the power and telephone wires. Such a wire affords maximum shielding when closely coupled to either the power wires or the telephone wires, when its conductance is high, and when its ground connections are of low resistance.

The variation of coupling with separation and with earth conditions is of great practical importance in the coordinated location of lines. Most of the subcommittee's study of coupling, therefore, involves field investigations of the variation of coupling with separation under different earth conditions, and is furthermore directed toward devising convenient and accurate methods of predetermining coupling in practical cases. Also, by studying and correlating experimental data derived under different conditions and from widely separated parts of the country, the subcommittee hopes to arrive at a better empirical basis for estimating coupling. Some of the work on this subject has already been presented.[1]

Factors Controlling the Frequency of Occurrence of Induced Voltages

The frequency of occurrence of induced voltages in paralleling communication lines, while chiefly dependent on the frequency of occurrence of faults on the power line, is also somewhat affected by the location of the exposure with respect to the location of neutral grounding points. For example, if there is only one neutral ground, faults occurring between it and the exposure will produce relatively little induced voltage.

The frequency with which faults occur is usually traceable to features of electrical and mechanical design, the character and amount of insulation, and the location of the lines. Specifically, the factors which appear to be responsible for the majority of faults on power lines are: poor configuration, inadequate spacing and clearances, inferior insulation, lightning, fog, smoke and dirt, birds and animals, proximity of lines to external objects apt to interfere with operation mechanically or electrically, and certain mechanical features of design affecting the strength of construction, such as ineffective anchors, guys, or conductor and ground wire supports, particularly at angles and dead-ends, and insufficient bearing areas of subsurface structures.

Factors Controlling the Duration of Induced Voltages

The length of time faults are permitted to remain on a power system is controlled by the kind of protective relaying employed and by the type and condition of the circuit breakers and other terminal equipment. The type of relay system, the degree of sectionalization obtained, the adequacy of the circuit breaker as to speed and rupturing capacity, and the maintenance of the equipment are the most important factors.

[1] For references see bibliography.

Generally, the type of fault has little effect on the duration if there is sufficient current to operate the relays. Conditions have been noted, however, where the fault is of such high impedance that the current is not adequate for the operation of the relays. Such high impedance faults usually occur on wood pole lines and may result in burning of pins, crossarms and poles. They may also occur on steel tower lines as the result of branches of trees getting in contact with conductors.

Effects Produced by Induced Voltages

Low-frequency and transient voltages induced on telephone circuits may produce a variety of effects depending upon their magnitude and duration. These effects include service interruption, false signals, telegraph signal distortion, damage to plant, electric shock, and acoustic shock.

Telephone circuits are very low energy circuits, the voltage for talking purposes rarely exceeding one or two volts, with maximum current measured in milliamperes. For signaling purposes a maximum of 165 volts peak, is used with currents limited to about 0.10 ampere. For telegraph service the voltages are limited to 135 volts between wire and ground, while the current is limited to less than 0.10 ampere. By contrast, the voltages due to induction, in some cases of exposure, may be a thousand volts or more.

Service Interruption.—When the telephone protectors are operated by induced voltage the behavior of the protector discharge gaps depends upon the magnitude of the voltage and current and the length of time the discharge lasts. In cases where the discharge is not promptly extinguished or where the current is very high, the discharge gaps may become permanently grounded. This causes interruption to service until the affected protectors can be replaced, the time necessary for such replacement depending, of course, upon the protector locations.

False Signals.—False switchboard signals are likely to be coincident with protector operation. They produce a bad service reaction due to operators answering false calling signals and cutting off connections because of false disconnect indications.

Distortion of Telegraph Signals.—The induced voltages appear in just the same paths over the wires as the operating voltages of grounded telegraph. The effect of such induced voltages depends on their magnitude, character, and duration. Voltages much lower than those sufficient to operate the protectors may cause detrimental effects ranging from a slowing down of speed to complete failure. Where the duration is short, the effect may be limited to distortion of signals, or, if the voltages are high enough, to momentary interruptions.

Damage to Central Office or Other Telephone Plant.—The dielectric strength of the telephone plant is adequate for the voltages used in communication service, with appropriate factors of safety, but higher voltages may sometimes, notwithstanding the protective devices, cause dielectric failure, thus damaging the plant, particularly cables and wiring or apparatus in telephone offices.

Electric Shock.—Telephone linemen in the course of their work upon wires at relatively close spacing, cannot avoid getting in contact with the wires and if the wires were subject to sufficient induced voltage, the men would be liable to receive electric shocks. On severely exposed lines such voltages are liable to occur at any time, suddenly and without warning. Electric shock might either injure a lineman directly or startle him and cause him to lose his hold and fall from the pole. Voltage to ground due to induction appears not only within the exposed section of line but considerably beyond. A similar, and in some respects worse, condition may exist with respect to employees working on cable circuits which are either exposed or directly connected to exposed circuits. In cables the wires on which the foreign voltage appears are very close to the grounded metal sheath and usually also to other wires at approximately earth potential, as well as to the earth itself. This problem has become more difficult with the rapid growth of the telephone and electric power systems and is engaging the subcommittee's serious attention.

Acoustic Shock.—Acoustic shocks are liable to occur with the breakdown of telephone protector discharge gaps, which temporarily unbalances the circuit and causes a sudden and abnormally large current in the receivers. This current gives rise to sudden and severe flexures of the receiver diaphram, which produce loud sharp noises in the ear of a person using the receiver. Telephone operators, due to the nature of their work, are particularly liable to acoustic shocks, the effects of which range from minor reactions to severe general disturbances of the nervous system which may be painful and of long duration. In addition, if danger of severe shocks exists, the operating force may become fearful and the impaired morale seriously affect the service.

Types of Protective Measures

The foregoing effects of induction from paralleling power lines may be reduced by: (1) measures in the power system to limit the influence, (2) measures in the communication system to limit the susceptiveness and (3) coordinated location of lines or other means to reduce the coupling. As a solution in a specific situation, one measure may be sufficient or two or more measures may be required, depending on the conditions. The solution should afford the necessary protection without hampering the development or operation of either system. Where there are two or more alternative solutions, the one which is best from the engineering standpoint, including both the technical and economic aspects, should of course be applied.

Cooperative planning in advance of construction is especially important in situations involving low-frequency induction, because of the wide ranges in magnitude both of coupling factors and of residual currents. By advance notifications of construction it is possible to bring up for analysis the low-frequency effects which the proposed construction would bring about and, if necessary, to agree upon changes in the plans to prevent or reduce these effects.

As to the physical dimensions and relations of power and telephone lines which constitute an exposure there are no blanket rules for guidance; each case requires specific consideration. Due to differences in geological conditions and other variable factors, a given length of parallelism at a given separation might give satisfactory results in one location, whereas an exactly similar physical relationship of lines in another location might result in the communication system being rendered inoperative at times of power system fault. This fact emphasizes the necessity of advance planning and cooperative study of situations as they arise. Such cooperation may easily lead to a satisfactory solution of situations which at first seem very difficult. On the other hand situations which at first appear devoid of any possibilities of trouble may on careful study be found to require protective measures.

Protective Measures for Power Systems.—It will be evident from the foregoing discussion that protective measures to reduce the inductive influence of power systems should be directed to limiting the magnitudes of unbalanced currents and voltages, particularly under abnormal conditions, and to reducing the duration and frequency of occurrence of abnormal conditions. Of such protective measures some are concerned with fundamental questions of line and system design and must be incorporated in the construction plans, while other measures are of such a character that they may either be incorporated in the original construction or added later if found necessary as a result of subsequent experience or developments in either the power or telephone system.

Fault-Resistive Design and Construction.—As mentioned in the paper by Messrs. Harrison and Silver the methods employed in reducing the frequency of occurrence of faults are primarily involved in the design and construction of the power line, i.e., adequate insulation, clearances, and spacings, and so arranging the component parts of the structure that the line will in effect be fault-resistive. Increasing demands for better service by the public combine with considerations of inductive coordination to justify greater attention to fault-resistive line construction.

Faults may result from improper guying of poles, i.e., guys so located that the spacing between guys and conductors is inadequate, or the path from insulator to crossarm brace and thence to the guy is insufficient to withstand the voltages imposed. The conductor spacing may be inadequate or the configuration of the circuits may be such that the sudden unloading of conductors coated with sleet will result in their whipping together, or, if a ground wire is used, it may be so located that the unloading of sleet will cause the conductors to whip into the ground wire, or the design of the line, either steel tower or wood pole, may be such that inadequate strength is provided for the mechanical loads incurred.

Attention is being given to the location of lines as a material factor in limiting the number of outages resulting from external sources, such as lightning, broken trees, blasting, and automobiles. For example, lines built in valleys are less subject to failures due to lightning and wind storms than lines built over hills.

There is little need to call attention to the grade of insulation employed on power lines as recent lightning studies and papers have emphasized the importance of rationalization of insulation throughout the plant. By this method it is hoped that preferential points of failure would be established, thus permitting prompt restoration of service without damage to expensive equipment since most of the faults would be confined to the line.

The amount of insulation to be employed on lines is affected by topographical and climatic conditions. Lines in areas relatively free from lightning or shielded from lightning disturbances may, of course, employ less insulation without increasing the number of faults. On the other hand, lines built in areas where lightning is prevalent may justify not only higher insulation but also, on steel tower lines, the use of ground wires as an additional protection. Areas where salt fog, smoke, or chemical fumes are prevalent require special treatment as to the form of insulation used.

Laboratory tests and limited field experience indicate that a proper utilization of the inherent insulating properties of wood in structures may result in considerable improvement in line operation. The subcommittee is investigating the service performance of wood pole lines of differing designs with a view to determining how much may be accomplished in reducing the number and severity of faults by suitable arrangements of metal braces, fittings, guys, etc., to avoid so far as possible shunting out the insulation of the wood.

To the experienced designer the protective measures to be employed on lines subject to frequent faults are obvious, namely, the rearrangement and reconstruction of the tower or pole top to obtain greater spacing between conductors or greater clearance between conductors and other metal parts. In some cases spacing and clearances would be materially improved by utilizing a triangular configuration so that the conductors are not likely to come in contact with each other or the ground wire when sleet or other conditions cause whipping or dancing of the conductors. In other cases, merely a relocation of the point of attachment of guys would improve conditions without materially decreasing the strength of the structure.

Fault-Current Limiting Measures.—Resistors, or reactors, in the neutral ground connection of a power system provide a means of directly limiting the magnitude of the residual currents, except in cases of double faults. In cases where the residual currents can be so far reduced as not to set up induced voltages of high values in the communication system without reacting unfavorably on power system operation, this method alone may afford a satisfactory solution. In such cases it has the further advantage of reducing the stresses to the power system due to the fault current. Where it is impracticable to clear up a situation by residual current limitation alone, this method may be effectively used in combination with other protective measures.

The reduction in residual current which will be brought about by adding a given amount of impedance in a neutral ground connection can be estimated with reasonable precision. It is not so much this question therefore, that requires study by the subcommittee as it is the question of the limitations and costs of this protective measure, and its reaction upon the power system. Included in this work is a study of the relative advantages of inductance as compared with resistance for accomplishing such current limitation. The subcommittee has under observation a number of installations of current-limiting devices and is engaged in experimental and theoretical studies and in field observations by means of recording instruments to determine the possibilities of this type of protection.

In non-grounded power systems a single fault on a phase conductor results in the charging current of the system flowing to earth through the fault. The other phases, rising to full line voltage above the grounded phase, create a system unbalance which may manifest itself by induction in paralleling communication lines. In such cases the problem is one of electric induction except for the magnetic induction set up by the charging current.

When double faults occur on either grounded or nongrounded systems, severe magnetic induction is liable to result and under these conditions it is difficult to limit the residual current.

Shielding. Ground wires on a power line, while tending to increase the total residual current, serve the purpose of shielding by reducing the strength of the external electric and magnetic fields set up by the residual voltages and currents. The net effect of ground wires from the low-frequency standpoint is to reduce the voltages induced in paralleling communication circuits under abnormal power circuit conditions. The effectiveness of such shielding depends on the impedance of the shielding conductor and its ground connections. Under favorable conditions the induced voltage at 60 cycles in paralleling communication circuits may be reduced about 40 per cent by this method. Such ground wires, if used on wood pole lines, have a disadvantage in that they impair to some extent the insulating property of the poles.

High-Speed Circuit Breakers and Relays.—Very sensitive high-speed relay systems have been developed which, together with high-speed types of circuit breakers reduce the time duration of a power line fault to approximately 1/10 second, as compared with one half second to three seconds required by the older forms of relays and circuit breakers, thus tending to minimize the effects of induction. On the other hand inadequate relaying, or the omission of automatic circuit breakers, may extend the duration of faults to a point where the hazards to power apparatus are serious. High-speed breakers and relays are expensive and it is difficult to justify them solely as a remedial measure for induction, particularly as the speeds of operation now available for relays and breakers on power systems, have not reached values which make them a complete solution of coordination problems. However, with the increasing size and interconnection of power systems, high-speed relays and circuit breakers are playing and increasingly important part in promoting power system stability.

Periodic testing of relays and circuit breakers accompanied by complete overhauling at regular intervals, will do much to reduce the duration of faults and to prevent improper functioning of the equipment.

The subcommittee is following the developments in high-speed breakers and relays with much interest. If such devices should come into general use for all classes of service it is expected that they would materially improve the whole inductive situation.

Improvement in Balance.—As mentioned above, low-frequency induction between power and communication lines is sometimes experienced under normal operating conditions. On grounded telegraph and signal lines the trouble usually manifests itself by a chattering of telegraph instruments or by false signals. Improvement in balance of the power line by transpositions will in some cases correct the difficulty.

Protective Measures for Communication Systems.—In general, measures applicable to the communication system to prevent or reduce the effects of induced voltages take the form of arrangements or devices for removing or counteracting the voltages to ground or the currents in the telephone circuits which might be produced by the induced voltages.

Bell System Standard Protectors.—It is Bell System standard practise to equip all telephone circuits which are exposed to the liability of foreign voltages, with electrical protective devices. These devices are made in various forms and combinations for different plant and exposure conditions. The protector used at central offices and at subscribers' stations includes a discharge gap which operates at approximately 350 volts and a fuse which opens the circuit at about 10 amperes. Such devices are intended to offer a measure of protection against lightning discharges and against the voltages and currents resulting from accidental contacts with foreign wires or from low-frequency induction.

In order to protect telephone linemen or others working on open-wire lines against electric shock from induced voltages, it is necessary that the voltages between line wires, and between each line wire and ground, be kept low. The use of protectors at central offices does not so protect the linemen as the impedance drop on the line wires permits high voltages between wires and ground at other points, such as the terminals of the exposed section.

It appeared however, that protectors of the Bell standard type might be used on open-wire lines at locations immediately adjacent to exposures to limit induced voltages to ground. A number of installations of this kind have been made but observations over a period of time show that they introduce serious troubles as the protectors, being subjected to heavy discharges, often become permanently grounded thus interrupting service. It also sometimes happens, as all the line wires are not always equally exposed, that some of the protectors operate and others do not, resulting in objectionable voltages between line wires.

Relay Protectors.—In view of the inadequacy of existing forms of protectors for such use, the subcommittee is experimenting with a "relay protector." This device includes Bell standard protectors in combination with a relay which operates to short-circuit them upon the occurrence of a discharge, thus relieving the protectors of the duty of carrying the large discharge current and greatly reducing their tendency to become permanently grounded. In more recent types all the relays at a protector point are electrically interlocked, so that when any relay operates all line wires are grounded within a few cycles.

Several trial installations of relay protectors have been made and are under observation. To guard against voltages to ground within the exposure these protectors have to be placed within, as well as at the ends of, the exposed section of line. Where the longitudinal induced voltage is large, protectors are required at a number of points within the exposed section.

The effective application of such protectors requires grounds of the order of one or two ohms and an important feature of the investigation is to devise methods of constructing and maintaining such grounds at remote points along the line.

The subcommittee is investigating in the field and in the laboratory the effectiveness, cost, reaction on service, and other practical questions relating to the installation and maintenance of this method of protection.

Acoustic Shock Reducers.—Since acoustic shock due to induced voltages involves dissymmetrical discharges across the two sides of the protector, efforts have been made to devise a protector which would break down and discharge symmetrically, i.e., provide two reliable low-impedance paths for heavy discharges, which would at all times have very closely the same arcing impedance. Thus far the subcommittee has not been successful in developing a practicable protector of this kind.

For the purpose of equalizing the voltages on the protector during the discharge period, an accessory device termed a "discharge balance coil" is under investigation. It consists of two equal windings on a common core, each in series with the discharge gap of one side of the line, and so arranged that the fluxes set up by the circuits in the two windings are in opposition. The "booster" action of this coil tends to equalize the discharge currents. This reduces acoustic shock from induced voltages, provided all protectors are so equipped and the line itself has no large unbalances. When however, voltage is impressed on one wire only of a telephone circuit, as by accidental contact, these coils have a detrimental effect on the action of the protector in reducing voltage to ground, as they introduce impedance in the protector discharge path.

Development work is also being conducted on other types of acoustic shock reducing measures which do not attempt to prevent unbalanced current but merely to shunt it out of the telephone receiving circuit. Obviously a device acting on this principle to be successful must be practically instantaneous in operation. One of the most promising of such devices consists of a high ratio step-up transformer with its primary connected directly across the receiver to be protected. The secondary is connected to a low voltage discharge gap. Any abnormal voltage across the primary operates the discharge gap and the transformer becomes a low-impedance shunt. A number of field trials of these reducers applied to operator's receivers have been made. While not affording the full degree of protection desired they have been found to reduce substantially the severity of acoustic shocks and it is believed that they will be of considerable benefit in cases where some form of protection against acoustic shocks to operators is urgently required.

Another device based on the shunting principle consists of opposingly poled copper oxide rectifiers connected across the receiver. These have the property of greatly diminishing impedance with increasing voltage. The problem is to obtain a sufficiently sharp change in impedance with voltage, while avoiding a normal impedance so low as to cause serious transmission losses. As an aid to this end, biasing batteries are under investigation.

The committee has also investigated the saturating characteristics of a vacuum tube for acoustic shock reduction. The properties of a vacuum tube are such that the output current cannot be increased substantially beyond a definite value regardless of the input voltage. This feature can be made use of to limit shocks by a design which will pass currents substantially without distortion up to approximately the highest value of signal current used, thus cutting down the shock voltages which exceed the normal signals. While quite effective, this method involves apparatus which is more bulky and expensive than the transformer and spark-gap type reducer. Telephone repeaters accomplish this result to some extent and are being investigated by the subcommittee, to determine the quantitative reduction of acoustic shock by this means under practical conditions.

In cases where toll or trunk lines are exposed, an acoustic shock reducing device which could be placed at the ends of the lines would have the advantage of protecting subscribers as well as operators. Development work to obviate certain difficulties in using such a device is under way.

An effort is being made to develop a telephone receiver which will saturate between the values of current required for effective speech transmission and values of current which produce acoustic shock. This requires a sharp bend in the saturation curve of the iron employed in the receiver magnetic circuit. Until the development of permalloy, this feature was not approachable, but experimental permalloy receivers have now been developed, and, while it has not yet been possible to achieve the end sought without serious sacrifice in transmission, work along this line is continuing.

Improved Insulation.—A slight reduction of susceptiveness to interference by low-frequency induction could be secured by providing increased dielectric strength to ground in communication circuits and their associated apparatus. Another method would be to insulate or isolate all conducting parts of the communication system so as to prevent contact by employees or others with wires or apparatus which may carry a dangerous voltage. Neither of these appear practicable at this time.

Drainage.—Drainage is a method for controlling the parts of the circuit in which the induced voltages appear and causing these voltages to be consumed in those parts where they are least harmful. This is accomplished by connecting the telephone conductors to ground, preferably through balanced impedance coils, at certain points throughout the exposure. Assuming low resistance grounds at the drainage points, the resulting voltage to ground at such a point after drainage is established is limited to a value corresponding to the voltage drop over the impedance of the coil and ground connection. If this impedance is small compared to the other impedances in the drainage section, the voltage to ground at the drainage point is a small part of the total voltage induced in that section.

Under present conditions, the application of drainage is limited to special situations where interference with circuit testing and maintenance is of relatively minor importance and where superposed d-c. telegraph and carrier telephone are not used.

Neutralizing Transformers.—The neutralizing transformer is a device for introducing into an exposed communication wire a voltage in opposition to the voltage induced by the disturbing circuit, thereby to a certain extent neutralizing the latter. The neutralization is effected by means of transformer action, the primary coils of the neutralizing transformer being connected to conductors which are grounded at the terminals of the exposure (or section of exposure), so that the voltage induced in these conductors will send currents through the transformer primaries. These primary currents induce in the secondaries of the transformers voltages substantially in opposite phase to the voltages induced in the telephone wires by the power circuit. The secondaries being connected in series with the exposed communication wires, the neutralizing action is obtained.

On account of introducing crosstalk and adversely affecting telephone transmission and carrier, application of neutralizing transformers has been confined chiefly to telegraph circuits. No applications of these devices to power line exposures have been made. They are, however, being studied by the subcommittee to see whether the objections mentioned above can be overcome and to determine their possible field of application.

Shielding.—Shielding on a telephone line may be effected by special grounded conductors, by working conductors, or by cable sheaths. Miscellaneous structures such as pipe lines or rails in the immediate vicinity of an exposure also introduce more or less shielding. The employment on a telephone line of a high conductance shield wire, well grounded at the ends of the exposure and at intermediate points, may reduce the induced voltage by as much as 40 per cent at a frequency of 60 cycles. As bearing on the prevention of electric shock from induced voltages on telephone lines, shielding has a disadvantage in that it may, depending somewhat on the method of construction, add to the chance of a lineman making contact with grounded metal.

Use of Cable.—A metallic sheath enclosing the conductors of a cable is a type of shielding. The lead sheath of a 2⅝ in. diameter aerial telephone cable, if effectively grounded at the ends, as when directly connected to an underground cable sheath, reduces the voltages induced in the conductors within the cable by about 50 per cent at 60 cycles. The additional shielding brought about by the surrounding earth when such a cable is placed underground is negligible at low frequencies, although underground construction has an advantage in affording a low-resistance ground for the sheath. The large number of conductors in a cable afford mutual shielding which varies from a negligible to a considerable amount depending upon many factors, important among which is the extent of the cable beyond the ends of the exposure. If two or more cables are close to one another through an exposure, each benefits by the shielding action of the others, so that the shielding increases with the number of cables.

If the lead sheath of the cable is surrounded by magnetic material as by armoring or placing cable in iron pipe, the shielding may be largely increased. With the form of iron tape armored cable referred to in the Harrison-Silver paper, which is now in trial use, shielding at 60 cycles is about 80 per cent, assuming effective grounding. Armoring a cable increases its cost substantially but has an advantage apart from shielding in that the cable being protected by the armor against mechanical injury may be buried directly in the earth without conduit. The armor is protected by impregnated wrappings but its life has yet to be determined. The shielding afforded by this type of cable has been studied experimentally under practical field conditions. Other installations and studies have been made abroad. It is probable that there may be a field of use for this type of cable in situations for which it is best adapted.

Coordinated Location of Lines.—Since the magnitude of induced voltages for given power line conditions depends upon the inductive coupling of the two classes of lines, which in turn is dependent upon their relative location, particularly their separation and length of parallelism, it is possible by advance cooperative planning of new power and telephone line locations to minimize and in some cases to forestall inductive effects in the telephone system. If the cost of remedial measures which inductive exposures would render necessary can be avoided, additional expense in locating lines to avoid such exposures may be justified and where a complete solution is obtained in this way both parties secure greater freedom in the construction and operation of their lines. However, with the rapid expansion of both services, the possibilities of complete solution by separation of lines alone are becoming more and more rare, particularly for lines along highways.

Coordination of Grounding Practises.—The occurrence of a fault on a power system usually results in raising the ground potential at the points of grounding as well as at the point of fault, but if steps are taken to coordinate the grounding of the power system and the telephone system serving the power company, particularly at transformer and generating stations, the effects in the telephone system of the earth potential gradient caused by a power fault may be minimized. For example, if in a switching station the same ground should be used for the power system neutral and for the telephone system, a power fault might cause the switching station ground to rise many volts above the distant telephone exchange ground, and result in operating the telephone protectors and possibly interrupting service. If, however, independent grounds sufficiently separated are used at the switching station, or an insulating transformer is placed in the telephone circuit, the power neutral ground may rise in potential without unduly affecting the telephone system.

Comprehensive consideration of the low-frequency coordination problem involves a study of the reactions between the grounding practises employed by power companies and those employed in telephone and telegraph systems. There is considerable diversity in practise with respect to methods of grounding. Some power transmission lines and primary distribution lines are not provided with any designed grounds, although most such lines have grounded neutrals and a few lines are grounded in such a way that operating current flows through the earth. In built-up communities there are underground pipes, cables, and other structures along which current in the earth will flow to a greater or less extent. These structures have varying degrees of conductivity and some of them have, either by design or by accident, high resistance joints. Consequently the paths of earth currents are exceedingly complex. The conditions as to earth currents and earth potentials necessary to be known in order to work out any coordinated scheme of grounding would usually have to be determined by tests.

The different kinds of grounds to be considered include those on: power transmission circuit neutrals, lightning arresters, power distribution primary neutrals, power distribution secondaries, railway systems, building conduits, telephone protectors, batteries, ringers, telegraph circuits, lightning rods, electrolysis protection systems, various types of signal circuits such as fire and police alarm systems, and so on. The grounding practises for all these different systems should be carefully studied and coordinated in order to prevent so far as possible harmful reactions among them. Such a study of course goes considerably beyond the scope of this subcommittee.

Comparison of Different Protective Measures.—The ideal protective measure would be one which furnished adequate protection and had no unfavorable reaction from an economic or service standpoint on the system to which it is applied. However, the work thus far has not disclosed any measure which fully meets this ideal.

The relative advantage of different measures resolves itself into a question of the best technical results which can be obtained at the least over-all cost. The solution of problems consists of finding measures which afford the highest degree of protection which is practicable and reasonable under the circumstances. In the investigation of a specific case it may be found that certain protective measures can be combined with other work in such manner that the cost is not wholly chargeable to coordination for the reason that other results of value are secured. For example, shielding may be obtained at small cost if improvement of performance of a transmission line justifies the installation of ground wires; or, the benefits of shorter duration of induced voltage by the use of high speed circuit breakers and high speed relays may be secured in connection with a program for improving the stability of power systems.

No other measure affords such complete protection against all effects of induction as adequate separation. However, measures applied to power systems such as fault current limitation which strike directly at the source of low-frequency induction are of a basic character and permit a closer association of the two classes of lines, a very important consideration in congested areas. Measures which affect only the frequency of occurrence of faults, or their duration, while very helfpul, are not as effective from a protection standpoint as measures which limit the magnitude of residual currents and voltages.

As to measures which would allow telephone circuits to operate through a strong inductive field, the use of lead-sheathed cable surrounded by magnetic material seems to offer the physical possibility of affording the most effective protection. Precautions would be required, however, to prevent the shielding structure itself from rising to a dangerous potential with respect to earth. On open-wire lines where the occurrence of high induced voltages cannot be prevented, some form of protector for limiting the magnitude of voltage to ground seems to be a logical line of development.

Devices such as acoustic shock reducers, which protect only against a single effect of induced voltages, do not afford a solution of most specific situations, but have to be used in combination with other protective measures. In many situations, no single protective measure is adequate and if the exposure is severe several may be required.

In considering the effects which a new exposure may produce, all the relevant factors are capable of advance determination except frequency of occurrence of induced voltages, which has to be estimated on the basis of experience or judgment and a statistical analysis of line failures.

Selection of measures to be employed in specific cases should be made with the above considerations in mind to the end that the best engineering solution may be obtained irrespective of whether the protective measures are applied to the telephone system, to the power system, or to both.

Reaction of Physical Exposures and Lightning on Low-Frequency Induction Problem.—As telephone circuits which are exposed to induced voltages may also be exposed to possible contact with power circuits and to lightning, any comprehensive scheme of protection must take into consideration the high currents resulting from contact and the high voltage due to lightning. In this connection there are some points of difference in the reactions on the protection scheme of induction, contact, and lightning.

Contacts between power and telephone wires may occur at crossings or conflicts or they may occur on joint pole construction as described in the paper by Messrs. Huber and Martin. In any event such contacts can occur only where the two lines are in close proximity, whereas in cases of inductive exposure, a fault outside as well as inside the exposure, may produce disturbances in the telephone circuits. Moreover, in cases of contact, wire or structure failures are generally involved while faults may cause induction which do not involve falling wires. Contacts impose on the telephone line the full voltage to ground of the power conductor at that point, whereas induced voltage is usually only a fraction of the power circuit voltage. This does not mean that the imposed voltages due to contact are always higher than those due to induction, because the majority of exposures to contact do not involve the higher voltage circuits while the opposite is true regarding inductive exposures. In cases of contact only part of the wires of the telephone line are usually involved whereas in the majority of induction cases substantially the same voltage is induced on all the wires. The voltages imposed on a telephone line by contact as well as those by induction may extend over the full length of the conductors involved.

In addition to the effects of contact between wires of the two systems, there is a distinct class of hazard to linemen of both utilities introduced by situations of insufficient clearance due to improper construction or inadequate maintenance on the part of one or both utilities.

Voltages on telephone lines by lightning produce effects somewhat similar to the effects produced by power lines but lightning voltages differ from the other voltages in that their duration is much shorter. Lightning makes necessary protector discharge gaps of very high speed of operation in order to prevent serious over-voltages on the telephone system, whereas contacts with power circuits make necessary a protector of high current-carrying capacity.

Committee's Program of Work

The program of work on low-frequency induction undertaken by the Joint Subcommittee on Development and Research through its project committees is laid out to develop the essential facts bearing on the problem of telephone protection in a broad sense, including causes, effects, and remedial measures. The program covers not only the technical but also the economic aspects of the problem. The problems of lightning and physical contact under conditions of conflict or joint use are also included, as the measures finally adopted must protect against voltages from these sources as well as voltages induced by power systems.

Extensive field trials of all promising protective measures, are under way in order to determine their practicability under operating conditions. As the work progresses, it is expected to issue from time to time reports covering the applicability, efficacy, limitations, and conditions of use, of various measures. This should result in a better understanding of the problem and more effective and economical solutions of specific situations as they arise.

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Status of Cooperative Work on Joint Use of Poles *

By J. C. MARTIN and H. L. HUBER

Because of the necessity of reaching the same customers, electric supply and telephone lines commonly use the same streets and highways. In urban communities, the joint use of poles for these two services has been very widely adopted and practises for joint use construction have been established from experience gained in past years. In rural communities, joint use is not always practicable or economical. Joint use involves many engineering and economic problems which have received the careful consideration of the Joint General Committee of the National Electric Light Association and Bell Telephone System.

This paper describes some of the problems which have been encountered in joint use, and briefly outlines the work which is being conducted by the Joint General Committee in connection therewith.

It is concluded that in specific cases proposed for joint use all factors should be studied cooperatively by the companies concerned and that everything practicable should be done to facilitate joint use construction and extend its usefulness.

TELEPHONE and electric light and power services are supplied in the same areas and to customers who are to a large extent common to both utilities. It is therefore necessary that both types of service be carried along the same streets and highways.

Experience has shown that safer and more satisfactory conditions can often be secured if the power and telephone circuits are carried on the same poles. This is due in part to the fact that clearances and climbing space can be more readily maintained where both classes of circuit are carried on the same poles rather than on separate poles on the same side of the street. Where separate lines are placed on opposite sides of the streets and alleys, it is difficult to secure and maintain proper clearances for service wires to buildings where these cross the line of the other utility.

Joint use of poles by the power and telephone companies results in the use of fewer poles on streets and highways and better appearance of aerial lines. It is, therefore, more desirable from the public point of view. It conserves pole timber and in many cases is more economical to both classes of utility than separate lines.

Because of the above mentioned advantages, joint use of poles by power and telephone companies has been widely adopted. No complete data are available as to the extent of such joint use at the present time, but it is estimated that there are at least five million poles jointly used by the power and telephone companies in the United States.

* Part IV of the Symposium on Coordination of Power and Telephone Plant. Presented at the Winter Convention of the A. I. E. E., New York, N. Y., January 26–30, 1931. Published in abridged form in *Electrical Engineering*, March, 1931.

Both of these classes of utility have been growing rapidly in the past twenty-five years and the development, design, and construction of the physical plant of each has kept pace with the growth in territory and number of customers served.

While earlier types of distribution plant were such that the possibility of contacts between wires of the two utilities and other hazards could be satisfactorily met by proper construction methods, protective devices, etc., later developments have increased the use of types of power distribution circuits regarding which questions frequently arise as to how service can be properly maintained and extended on jointly used poles.

These questions have received and are receiving careful consideration by the Joint General Committee of the National Electric Light Association and Bell Telephone System. This committee has recommended certain principles and practises for the joint use of wood poles which are intended for use as a basis on which electric supply companies and communication companies should work out their mutual problems and has undertaken important research work in connection with these matters through its Joint Subcommittee on Development and Research.

The principles and practises mentioned were presented in a report of the Joint General Committee under date of February 15, 1926, and while it is beyond the scope of this paper to consider these principles in detail, the following recommendations are of interest in that they indicate the way in which this matter is generally being approached:

Each party should:

(a) Be the judge of the quality and requirements of its own service, including the character and design of its own facilities, both now and in the future.

(b) Determine the character of its own circuits and structures to be placed or continued in joint use, and determine the character of the circuits and structures of others with which it will enter into or continue in joint use.

(c) Cooperate with the other party so that in carrying out the foregoing duties, proper consideration will be given to the mutual problems which may arise and so that the parties can jointly determine the best engineering solution in situations where the facilities of both are involved.

It will be observed that while each party retains full responsibility for facing and meeting its own problems, it is recommended that both parties cooperate in working out mutual problems involving the joint use of poles and in finding the best over-all engineering solution in each situation. These are among the most important of the principles which have been recommended and are the basis upon which practically all cooperative work is being carried forward.

It is the purpose of the following paragraphs to describe what has been done and what is being done by the Joint Subcommittee on Development and Research in connection with the engineering and economic problems which have been encountered in joint use work.

Construction Practises

Joint use construction practises have undergone almost continual change and improvement from the time joint use was first adopted and continued development is to be expected in the future. However, many of the fundamental requirements for securing satisfactory conditions on jointly used poles were recognized at an early date and form the basis for present day practise.

In the matter of relative levels it has been recognized that power wires should as far as practicable be carried in the upper position. In general, they are larger and stronger than the telephone wires. This is inherently so because of the current carrying capacity required. Placing power wires in the upper position on jointly used poles avoids the necessity of telephone linemen climbing through power circuits, the exact nature and characteristics of which they are not always familiar with.

Clearances must be provided which give sufficient space below the power wires so that power linemen will not have to come in contact with telephone wires while they are working on power wires. This neutral space must also provide sufficient clearances above the telephone equipment so that telephone linemen may work on the telephone plant without danger of coming in contact with power equipment. Clear climbing space must also be provided so that linemen may climb poles without having to be extremely careful to avoid falls or contacts with circuits from which they may receive physical injuries.

Fig. 1 shows one method for securing satisfactory conditions on a jointly used pole carrying circuits which both the power and telephone groups have recognized as being suitable for joint use.

In the matter of mechanical strength, joint use follows the practise in the construction of separate lines. That is, strength of construction should be provided such as to stand, with reasonable factors of safety, storm conditions which experience indicates are likely to occur from time to time in any particular area.

With regard to the matter of insulation and electrical strength, practises as to the size and type of power insulators have followed developments in the general field of power construction. Wires to street lights and underground connections to aerial plant require vertically run wires on jointly used poles. The location, insulation and mechanical protection of these have received special consideration to eliminate hazards to workmen.

Sufficient clearances between vertically run circuits of one type and the equipment of another utility on jointly used poles have also been

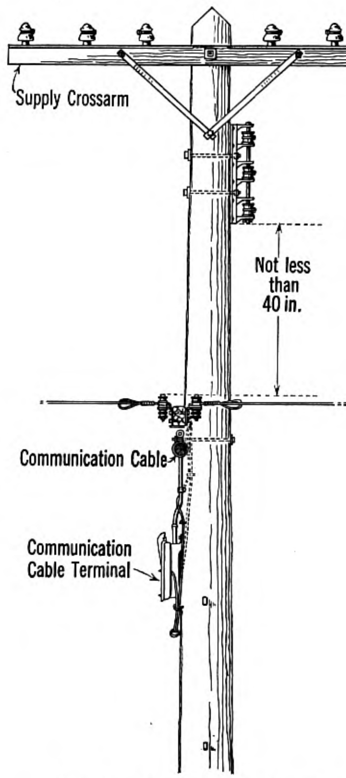

Fig. 1—Typical jointly used pole.

found to be very important from the standpoint of avoiding interruption to power and telephone services.

In the course of electrical storms, lightning may induce high voltages on either supply or communication wires. If the separation between the supply and communication facilities is not adequate at any point, these induced voltages may break down the insulation and arc between the two as illustrated in Fig. 2. Damaged plant may, of course, result from lightning alone. However, when lightning has established an arc between the power and communication circuits the normal voltage of the supply circuit may maintain the arc. This results in the transfer of power into the telephone plant at voltages which may be well above that for which it is insulated and may cause trouble on both the power and telephone system. This sort of abnormal belongs to the general class that includes insulator flashovers, short circuits on cables, tree grounds and similar power system occurrences that always carry the probability of damage to the power system or service.

While vertically run attachments with improper clearances have played a large part in causing such occurrences, any situation where

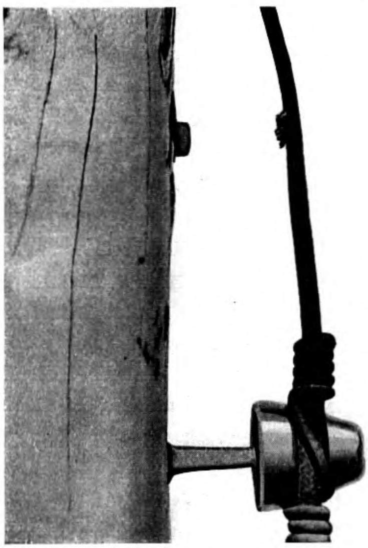

Fig. 2—Frayed insulation showing breakdown of insulation between power and telephone plant.*

insufficient clearance between power and telephone facilities is provided may result in similar trouble.

Emphasis has, therefore, been placed in present day standards on the necessity of maintaining proper clearances as well as strength of construction to prevent this kind of abnormal. Experience has shown that where these clearances are adhered to this type of abnormal is kept to a reasonable minimum.

The Joint General Committee is giving careful consideration to the matter of construction standards on jointly used poles. Pending the development of complete specifications covering recommended prac-

* In order to obtain a satisfactory photograph of the points of arc the vertical drop has been straightened out so that the clearance shown is much greater than existed at the time of the arc.

tises under various conditions, they have recommended the National Electrical Safety Code to be used as a guide to practise.

Protective Devices

Both telephone and supply circuits are equipped with protective devices which are fundamentally the same in principle. They may be divided into two general classes:

1. Those which provide protection from abnormal voltages consisting of protector blocks in the telephone plant and lightning arresters in the supply system.
2. Those which provide protection from abnormal currents consisting of heat coils and fuses in the telephone plant and fuses and circuit breakers in the supply systems.

These protective devices are a secondary defense against abnormal conditions which it is impracticable to avoid either by design or through adherence to construction standards.

Even when all practicable precautions with regard to clearances, strength of construction and insulation have been taken, accidental breaks occur in both power and telephone wires. In some cases there are direct contacts between such wires. Higher than normal potentials are also introduced into the telephone and power circuits by lightning and other causes.

It is because of the limitations of protective devices and other protective measures that joint use with certain types of circuits has been in question. Considerable differences of opinion exist between engineers as to the degree of hazard involved in joint use between telephone plant and power circuits of various types, voltages, and connected power. The problem has increased in importance as the use of higher distribution voltages and greater generating capacity have been employed.

This matter is under investigation by the Joint Subcommittee on Development and Research. Studies are now in progress in one rural area and in one suburban area to determine the over-all advantages and disadvantages of the use of higher distribution voltages and of joint use with these voltages under present conditions.

The first experimental work done by the Joint Subcommittee in connection with these problems was a detailed study of the characteristics of various types of fuses. This study covered all of the well known commercial types of telephone fuses and a number of experimental models. The operating characteristics of these fuses were obtained at voltages of 2300, 4000, 7500 and 13,200. The current range was from 16 to 1000 amperes. These tests were carried on in a laboratory where 20,000 kv-a. of generating capacity was available. The tests showed the dependability that could be placed upon the various fuses for interrupting voltages of the range from 2300 to 13,200 volts. They showed under what conditions the fuses could be depended upon and the ranges where the available type of fuses could not be depended upon for safe operation.

A number of the experimental models showed considerable promise of improvement over existing models, and this work will be carried further to determine what improvements can be made in the operating characteristics of fuses.

The next phase of the problem taken up included a study of the operating characteristics of various types of overvoltage protectors suitable for use on communication circuits. The experimental work covered breakdown with direct current, 60-cycle alternating current and a complete study with a cathode ray oscillograph of the behavior under steep wave fronts for carbon block protectors, neon and vacuum tubes.

These tests showed that the carbon block protector has a breakdown point with all types of applied wave fronts which is sufficiently fast and low to protect the insulation that is now used in the communication plant, as shown by similar tests on condenser and cable paper. The shortcomings of these blocks lie in their tendency to permanently ground the circuit when carrying current for any appreciable length of time.

The tests with steep wave fronts were carried to a rate of rise of 36,500 volts per microsecond, and it was determined by tests of propagation of steep wave front voltages through telephone cable that it was practically impossible to subject the plant to voltages with any faster rate of rise than those used in the protector tests.

The problem of adequate protection of the telephone plant in joint use, obviously, cannot be solved by the development of the telephone protective devices alone. The protective devices in the power system are equally important.

One of the important functions of the power system protective devices is that of clearing power system faults in a reasonable time interval. Obviously, telephone protective equipment cannot be expected to prevent damage to telephone plant in case of contact between the wire circuits of the two utilities when power system protective devices fail to operate and the physical contact of the circuits is maintained over an indefinite period of time.

One problem in the development and research work is the fixing of the part that the protective devices on each system must play in abnormal conditions. It is necessary that the over-all protective equipment be adequate and that the burden of overcoming weaknesses in the protective equipment of one system be not thrown on the protective equipment of the other. There are inherent limitations in both classes of protective equipment that must be defined.

Therefore, the next step in this investigation is a determination of the over-all characteristics of power circuit and telephone circuit protection under typical conditions of contact between the two plants.

While protective devices are an important element in connection with joint use involving certain types of power circuits employing the higher distribution voltages, there are also other important considerations. The general insulation of the telephone plant must also be considered, especially in connection with drop loops attached to and entering subscribers' premises. These matters are also being studied by the Joint Subcommittee.

All of these problems, as is the case of others being studied by the Joint General Committee, are being approached on the basis of determining the best over-all engineering solution such that both systems can provide their services in the most convenient and economical manner.

Inductive Coordination

In the early history of joint use, noise induction problems involving street lighting circuits appeared. Other interesting problems were encountered such, for example, as the accidental grounding of one corner of an isolated delta power system with its resulting unbalanced voltage inductive effects on open-wire telephone circuits, which type of telephone construction then predominated.

As these problems arose they received careful study and with the development and extended use of telephone cables and the use of improved operating methods in power and telephone distribution generally, inductive coordination of power and telephone distribution systems in the urban communities became less troublesome and did not for a time receive any large amount of consideration.

However, during recent years the introduction and extended use of various types of multi-grounded distribution systems described in the paper by Messrs. Harrison and Silver and the existence of certain types of signaling on local telephone circuits, have contributed toward making important the consideration of noise inductive effects in connection with joint use. This matter is discussed more fully in the paper by Messrs. Harrison and Silver.

The technical factors involved in inductive coordination problems under joint use conditions are complicated. The details regarding these factors and the results of the extensive studies of these matters by the Joint Subcommittee on Development and Research are described in the paper by Messrs. Wills and Blackwell.

The various operating problems which have arisen almost since the birth of the power and telephone industries and the investigations conducted by the Joint Subcommittee on Development and Research indicate the importance of giving careful consideration to the inductive coordination features of joint use and of including this factor in studies of the relative advantages and disadvantages of joint use as compared with separate lines. This factor should, of course, be considered from both its technical and economic aspects.

Much can be accomplished in the inductive coordination of the two distributing systems by cooperative advance planning. In urban areas where the telephone circuits are largely in cable, there is about a two to one ratio in the inductive effects between a joint line and separate lines across the street. In rural areas where the telephone circuits are largely open wire, the ratio of the inductive effects on joint lines as compared with separate lines across the highway, is much greater, other things being equal.

In urban areas the power and telephone companies can through cooperative planning frequently arrange to establish important power feeders and telephone circuits on separate streets and thereby avoid large inductive effects and permit more extensive joint use of branch lines. A careful review of the equipment used on the power and telephone circuits and the introduction of operating practises designed to limit the inductive susceptiveness of the telephone circuits and the inductive influence of power circuits, form an important part of advance planning and cooperation.

As described in the paper by Messrs. Wills and Blackwell, these latter factors include such items as limitation of the odd triple frequency series arising in Y-connected generators feeding directly on the line and in single-phase service transformers. Suitable limitations of the unbalances existing among the loads connected between the three-phase conductors and the neutral, limit the ground return components.

Grounding of aerial telephone cable sheaths to provide for increased shielding and the use of central office and station equipment providing a higher degree of balance with respect to ground are helpful.

The matter of joint use may involve both rural and urban communities. It is more generally associated with the latter because of the severe limitations in physical space available for utility use. In the case of rural lines where the telephone circuits are largely in open wire and the exposures between particular circuits are likely to be long, joint use is not always practicable. In these cases locations for separate lines are usually available.

Furthermore, joint use in rural areas is not always economical from a purely construction standpoint due to the fact that relatively longer spans can often be used on the power lines and both utilites are able in many instances to use shorter and lighter poles than would be practicable in joint use. Joint use with telephone toll circuits or power transmission lines has not, in general, been found desirable. Types of construction vary so widely and service requirements and inductive effects are such that it becomes uneconomical to carry out such construction.

Conclusions

Joint use of poles by power and telephone companies has many advantages, both from the standpoint of the public and from the standpoint of the wire using companies. This is especially true in built-up communities.

Important problems brought about by developments in practises, particularly in the use of high voltage distribution, remain to be solved.

Careful adherence to generally accepted practises with regard to clearances, strength of construction, insulation and inductive coordination is necessary in order that the advantages of joint use can be secured.

In considering specific cases proposed for joint use, it is advisable that all of these factors be studied cooperatively by the companies concerned, to the end that good service, safety and economy by both classes of utility may be promoted.

It is important that everything practicable should be done to facilitate joint use construction and extend its usefulness. The Joint General Committee of the National Electric Light Association and Bell Telephone System is continuing its efforts in this connection.

Symposium on Coordination of Power and Telephone Plant

Closing Remarks *

By B. GHERARDI

THE papers which have been presented here today bring out clearly the progress which has been made by the power and telephone companies in the study and development of methods for coordinating their facilities. It seems to me that this is an outstanding example of what can be accomplished through joint study and cooperative methods generally.

This work illustrates also the way in which the field of activity of the engineer is broadening. While the main duty of the engineer may still be the application of physical laws to accomplish the most satisfactory results in the most economical manner, the very organization of society which has resulted from these applications of physical laws, requires the engineer, if he is to play his full part, more and more to include in his considerations the broad economic and human factors which govern the success of social and business enterprises. In the work described in this symposium the approach has been not only the consideration of the complicated technical questions involved, but the working out as well of these questions on the basis of good business relations between two large utilities, having in mind that both have the responsibility for providing important services to the same public.

I would like to reiterate certain fundamentals which have played an important part in bringing about the present satisfactory situation. First, is that of getting together and getting acquainted, to the end that frank and friendly discussions will be promoted and misunderstandings avoided. Second, is the continued development of technical information for the coordination of power and communication systems adequate to keep pace with the rapid amplification and growth of these two services. Third, is a desire on the part of the companies concerned to work out each case in accordance with the best over-all engineering solution as though both utilities were under the same management. Where there is such a desire, the working out of the job is largely a matter of detail and results are assured which will be fair to all concerned.

We feel that the results of the cooperative work have been good from every point of view, and I want to express the appreciation of the Bell

* Presented at the Winter Convention of the A. I. E. E., New York, N. Y., January 26–30, 1931.

System people of the broad spirit of cooperation in which this matter has been approached by the power companies. I heartily join with Mr. Pack in his feeling of satisfaction for having taken part in the initial work which has brought about the present fine relations between the power and telephone companies and the effective handling of the various types of situation involving coordination.

Overseas Radio Extensions to Wire Telephone Networks *

By LLOYD ESPENSCHIED and WILLIAM WILSON

The development of intercontinental telephony through the agency of radio links connecting between the land networks is traced and its present trends indicated. A description is given of the facilities employed by the Bell System for overseas connections and connections to ships at sea. The transmission results secured with these facilities are set forth and some peculiar short-wave phenomena discussed. International problems of frequency use and conservation are briefly summarized. A fairly comprehensive bibliography of technical papers on transoceanic telephony is included at the end of the paper.

Introduction

THE progress which long-distance electric communication is making in tying the world together is perhaps nowhere more interestingly illustrated than in the developments which are now taking place in the interconnection of widely separated wire telephone networks by means of overseas radiotelephone links. It was only a few years ago, in 1927, that telephone service was first extended across the barrier of the North Atlantic and a beginning made in the interconnection of the great telephone networks of North America and of Europe. Rapid progress has been made since then in the further development of the North Atlantic facilities and in the extension of radiotelephone links from these wire telephone networks outward in other directions, until today such links span a large portion of the globe.

Since it is the nature of telephony that the circuits are employed personally by the telephone users it is necessary that these interconnecting links be of a high standard of transmission effectiveness and be free from interference. Also it is important that they be reliable in operation and continuously available during the operating periods, for the usefulness of telephone service is in part dependent upon its being immediately available on call. Although these requirements are not yet being fully met, the circuits already in operation are very effective and are proving to be valuable additions to the world's communication facilities.

The progress which is being made and the problems which are arising in the establishment of these systems and in the coordination

* Presented before Fifth Annual Convention of the Institute of Radio Engineers, August, 1930; Proceedings of I. R. E., February, 1931.

of them into a world-wide telephone network appeal to the imagination and challenge the best efforts of communication engineers. Especially is this development of interest to radio engineers since in this pioneering stage the interconnecting links are being forged by radio. Work is also going forward in the development of new types of submarine telephone cables for this purpose and undoubtedly such cables will in time play a large part in fortifying the more important of the world routes. The radio part of the picture is, however, quite enough in itself and this paper is, therefore, largely confined to this phase of the subject.

There is given first, a sketch of the wire telephone networks and the interconnecting links as they exist today, second, a picture of the transmission results which are being obtained in the operation of some of these overseas links, and finally, a discussion of the more important phenomena and problems involved in the radio transmitting medium.

The Existing World Telephone Picture

A simplified picture of the present telephone development of the world is given in the map of Fig. 1. Only the principal areas of telephone development are indicated, by the shaded portion, and only the more important routes of the wire networks have been sketched in. The figures give the approximate number of telephone subscribers in each continental area.

It is, of course, these networks which give direct access to millions of people in offices and homes and permit of the personal contact which characterizes telephone communication. It is natural, therefore, that they should be the foundation of the world-wide system which is growing up. The larger of these networks already spread over national boundaries so that the engineering problem is primarily one of interconnecting the networks, generally comprising groups of countries, rather than that of directly interconnecting by radio all of the component countries. The points within each network at which the interconnections are made may be expected to be determined largely by considerations of traffic and of operating efficiency. The differences of time and of languages between these widely separated areas, and, of course, the expense of providing reliable interconnections over these distances, are factors which will naturally limit the volume of use to be made of these connections. That they are destined to fulfill a very real need is already proven, however, by the services which are now being given.

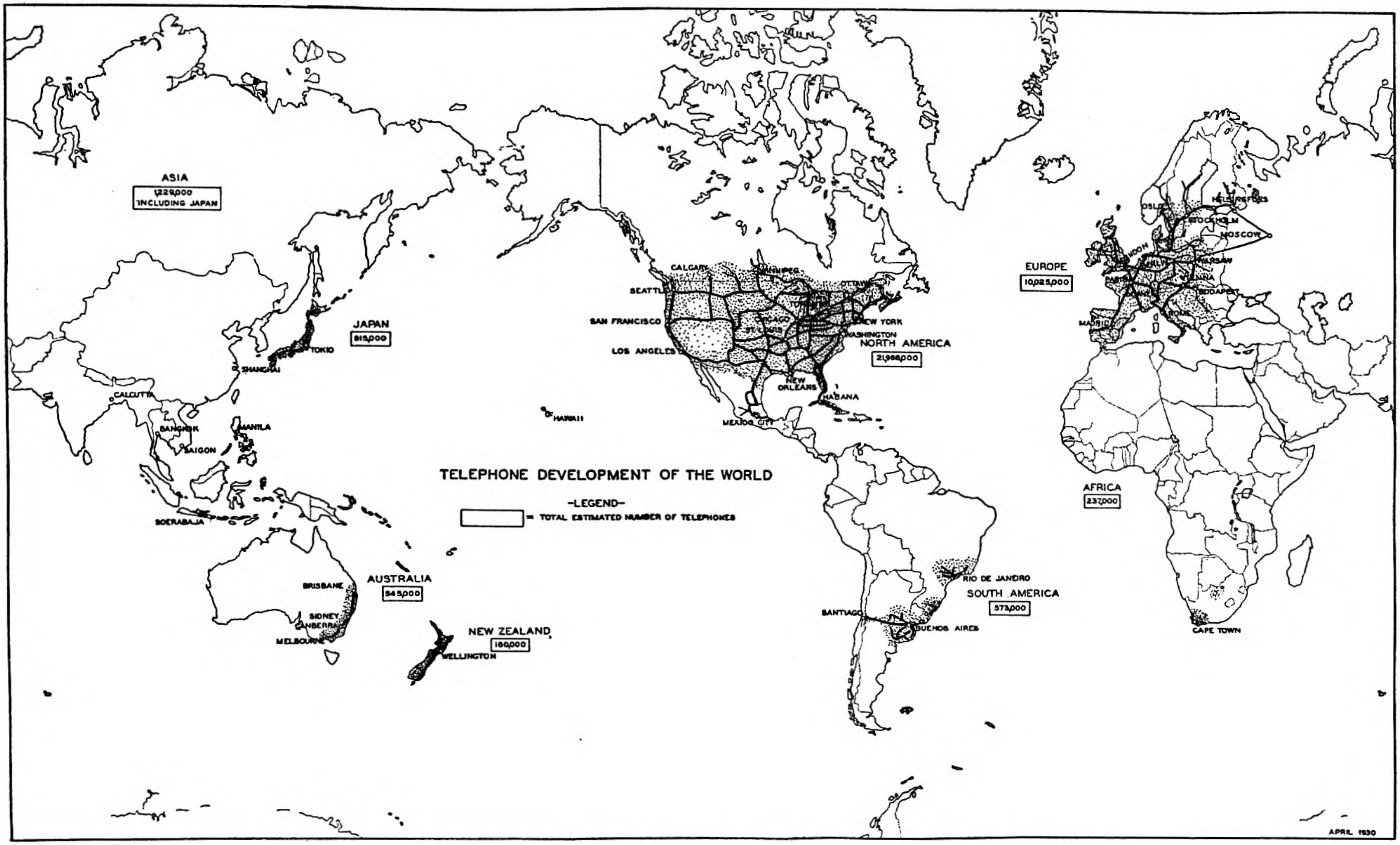
TELEPHONE DEVELOPMENT OF THE WORLD
-LEGEND-
= TOTAL ESTIMATED NUMBER OF TELEPHONES
ASIA
1,229,000 INCLUDING JAPAN
JAPAN
815,000
TOKIO
SHANGHAI
CALCUTTA
BANGKOK
SAIGON
MANILA
SOERABAJA
AUSTRALIA
545,000
BRISBANE
SIDNEY
CANBERRA
MELBOURNE
NEW ZEALAND
160,000
WELLINGTON
HAWAII
NORTH AMERICA
21,986,000
CALGARY
WINNIPEG
SEATTLE
SAN FRANCISCO
LOS ANGELES
OTTAWA
NEW YORK
WASHINGTON
NEW ORLEANS
HABANA
MEXICO CITY
SOUTH AMERICA
573,000
RIO DE JANEIRO
SANTIAGO
BUENOS AIRES
EUROPE
10,025,000
OSLO
HELSINGFORS
STOCKHOLM
MOSCOW
LONDON
PARIS
WARSAW
BUDAPEST
MADRID
ROME
AFRICA
237,000
CAPE TOWN
APRIL 1930

Fig. 1

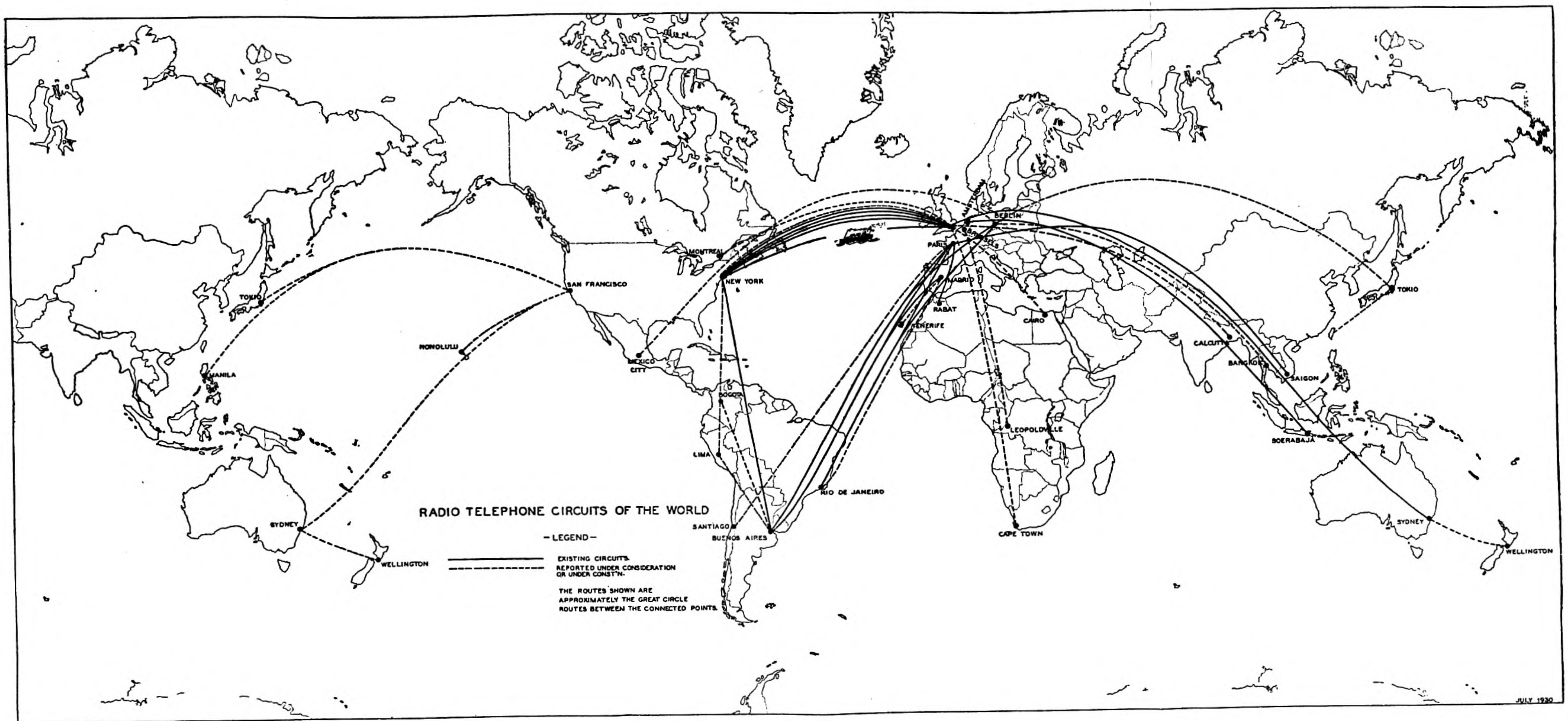
RADIO TELEPHONE CIRCUITS OF THE WORLD
— LEGEND —
EXISTING CIRCUITS.
REPORTED UNDER CONSIDERATION OR UNDER CONST'N.
THE ROUTES SHOWN ARE APPROXIMATELY THE GREAT CIRCLE ROUTES BETWEEN THE CONNECTED POINTS.
TOKIO
MANILA
SYDNEY
WELLINGTON
HONOLULU
SAN FRANCISCO
MEXICO CITY
MONTREAL
NEW YORK
BOGOTA
LIMA
SANTIAGO
BUENOS AIRES
RIO DE JANEIRO
PARIS
BERLIN
MADRID
RABAT
TENERIFE
CAIRO
LEOPOLDVILLE
CAPE TOWN
CALCUTTA
BANGKOK
SAIGON
SOERABAJA
TOKIO
SYDNEY
WELLINGTON
JULY 1930

Fig. 2

Development of Interconnecting Links

The present status of the development of these transoceanic radiotelephone links is illustrated in Fig. 2. There are shown the circuits which are in operation and also the projects which have been reported as under consideration or under construction. These telephone paths will be observed to correspond in general with the routes followed by the ocean telegraph and radiotelegraph services, in fact with the trade routes of the world, along which community of interest has been built up. Thus a certain orderly arrangement of the services is being realized naturally.

In general, there may be said to be five major groupings:

1. The North American-European connections. These are, of course, of outstanding importance because of the economic and social interest which exists between the two continents and because they connect with the large telephone wire networks on both sides of the Atlantic. North America and Europe combined account for about 32 million telephones out of a world total of about 35 million. The present situation on the North Atlantic route is discussed later on.
2. North America-South America.
3. South America-Europe.
4. Europe to Africa, Asia, and Oceania. The connections to Africa and to Oceania represent the interest which some of the European nations have in associated commonwealths and in colonies.
5. North America to Pacific points and the Far East. These are in the construction and project stage.

Most of these services are being given on a part time basis although that across the North Atlantic has been found to require 24-hour service and that between North and South America is for the full business day. Some of the circuits from Europe to South America and to the East Indies are not yet connected fully into the wire telephone network. The circuits which are in operation between South America and Europe instead of connecting into the European network by means of a single station are shared on a part time basis by several stations located in different countries in Europe, as is indicated by the forked lines in the figure.

One advantage of the use of radio for these services, particularly in this pioneering stage during which traffic over many of the routes is likely to be small, is the ability to share the use of a transmitting channel as between a number of receiving points where wire lines are not available. A representative case of this kind would be that of an important central station linked with a continental wire network from which it is desired to establish connections with a number of smaller outlying points. This possibility is not as simple as it may appear, however, because there enter the problems of directive antennas, of shifting frequencies if widely different distances are involved, and of not permitting the return transmission to be materially weaker than the outgoing transmission which means the use of relatively powerful stations at the outlying points. In general, these short-wave stations represent rather large investments and in working out interconnecting arrangements of this kind it is important to fit together the schedules at the various stations so as to minimize lost circuit time and to avoid leaving stations in idleness.

North Atlantic Facilities

Of the four circuits which now exist across the North Atlantic, as indicated in Fig. 2, one is the long-wave circuit, with which the service was originally started, and three are short-wave circuits. The dashed line, shown in the figure, between New York and London indicates an additional long-wave circuit which is planned. There is also indicated in the figure the ship-to-shore telephone service on the North Atlantic which connects with the land line network on either side.

The transatlantic long-wave system has already been the subject of technical papers [1] and need not be described in detail. It operates on a single side-band carrier suppression system in a frequency band centering at 60 kc. The single side-band system is used to minimize the frequency space occupied. The single band is used alternately for transmission in the two directions by means of voice actuated switching devices at the New York and London terminals. For the purpose of minimizing the principal limitation of long waves, that of "static," the receiving stations are located as far north as is reasonably possible and use is made of directive receiving antennas.

The three short-wave circuits which have been provided on the North Atlantic route add materially to the traffic capacity but are erratic in their behavior and their usefulness is dependent, in a large measure, upon being operated in combination with the more stable long-wave circuit. All three short-wave circuits are affected similarly by the adverse conditions accompanying magnetic storms, whereas long-wave transmission is not materially affected by these conditions except at night.[2] The second long-wave circuit is planned to provide a more balanced combination of facilities as well as to add to the total

[1] See attached bibliography.
[2] Bibliography 6, 14, 15.

circuit capacity across the Atlantic. In this connection, it should be noted also that a new type of submarine telephone cable is under development and is planned to be laid across the North Atlantic when completed. While this cable will provide only one two-way circuit, it is expected to be free from atmospheric disturbances and to fortify greatly the telephone service between North America and Europe.

The ship-shore telephone service which is being given on the North Atlantic includes a land station connection with the land line network in both the United States and in England and through these land stations service is given to most of North America and Western Europe. Four of the larger transatlantic vessels are equipped. The service may be expected to include in time additional shore stations and many other vessels. It is an example of a class of service for which radio alone is available, that of extending telephone service to moving craft at sea or in the air.

Short-Wave Technique

With the exception of the long-wave circuit across the North Atlantic, all of the links indicated in Fig. 2 are of the short-wave type. As to these different short-wave stations throughout the world, there is, of course, considerable difference between them in the requirements which are being met and the performance obtained. However, the same fundamental principles are being followed in all of the countries and the short-wave telephone technique may be said to be rather remarkably alike throughout the world. Transmission is on the ordinary double side-band basis since the necessity for narrowing the band is not of great importance in the present state of the art and the difficulty of single side-band operated at high frequencies is very much greater. In general, the transmitters are of the vacuum tube type employing master oscillators which are stepped up in frequency and in power for the final transmission; directive antennas are employed for both transmitting and receiving, and in the receiving apparatus use is made of the double detection principle with its advantages in giving stable operation with high amplification and high selectivity.

In the case of the radiotelephone stations which connect with the United States, the short-wave technique is further characterized by the use of transmitting sets which are provided with a piezo-crystal oscillator with temperature control for stabilizing the transmitting frequency, and the use of interchangeable coils which permit the frequency of the transmitter to be changed in keeping with the requirements for the different times of the day and year. The carrier output of 15 kw. corresponds to a peak output of about 60 kw. The final power stage of such a set is shown in Fig. 3. The units marked 1, 2, and 3 are the water jackets for three of the six double-ended, 10-kw. tubes, the other three being on the other side of the mounting. The circuit is of the push-pull type.

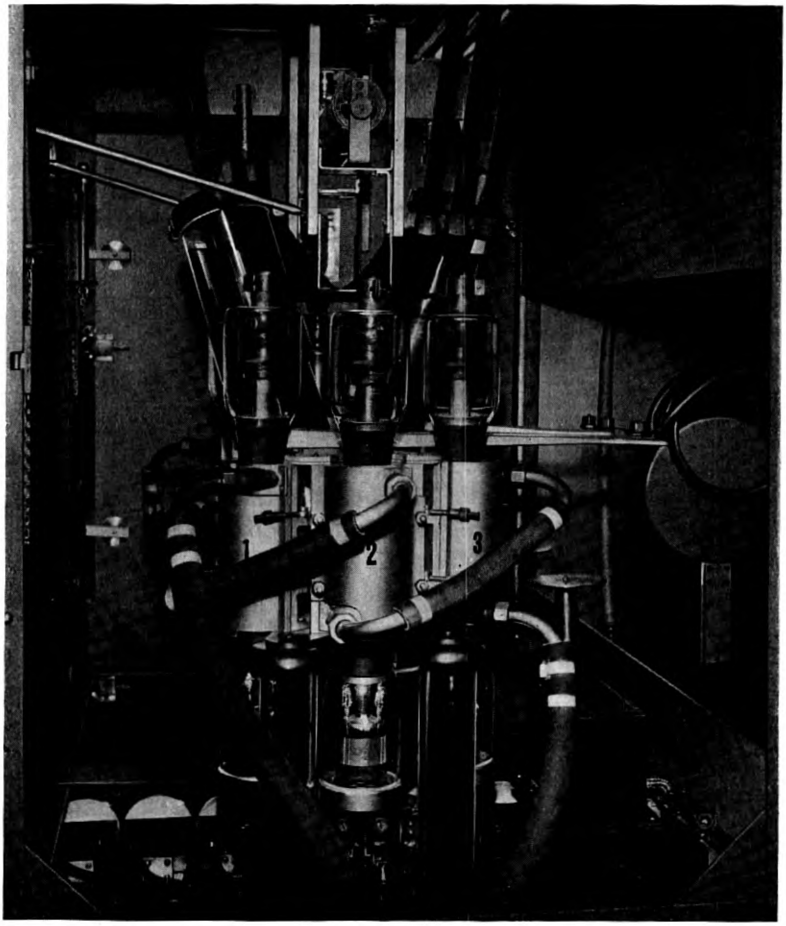

Fig. 3—Short-wave radiotelephone transmitting center of the American Telephone and Telegraph Company, Lawrenceville, N. J. Six 10-kw. tubes used in one of the output stages of a transmitting set. Coupling coils on right, monitoring amplifier boxes at lower right.

The radio receivers employed in the United States are built so as to have low intrinsic noise and sufficient gain to enable very small field strengths, of the order of 1 μv. per m., to be detected and raised to the required telephone speech level. They are equipped with automatic gain control which minimizes the fading variations in speech volume. One of the radio receivers employed at the Netcong, N. J., receiving station is illustrated in Fig. 4. The antenna leads are brought in beneath the floor in the concentric pipes which are seen to

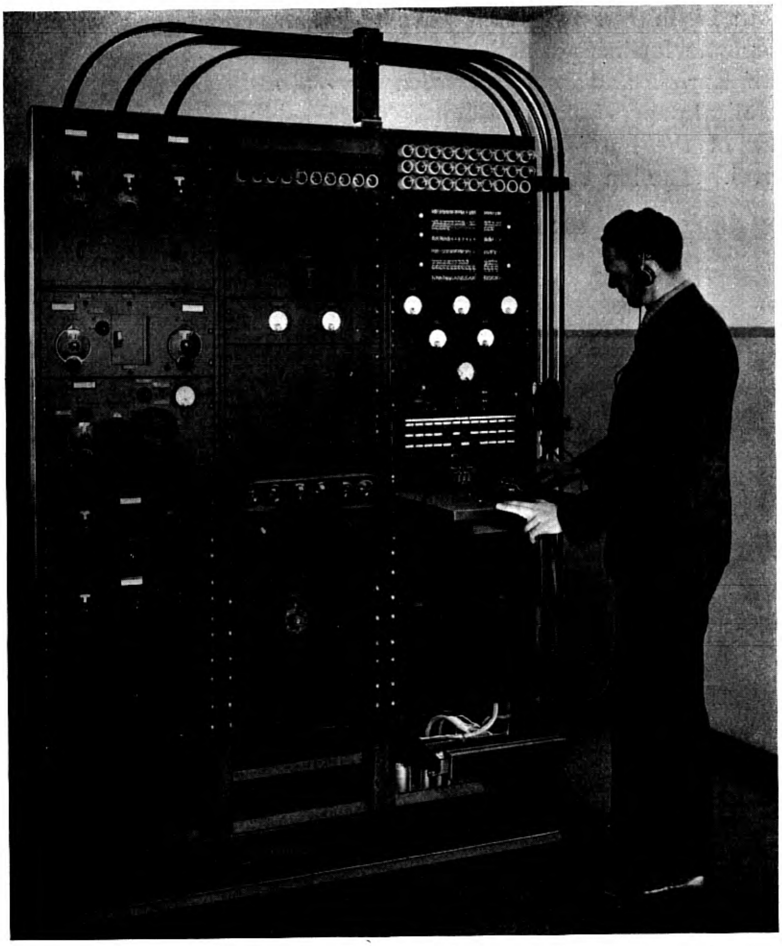

Fig. 4—Short-wave radiotelephone receiving center of the American Telephone and Telegraph Company, Netcong, N. J. Radio receiver for South American circuit. Antenna concentric pipe transmission lines enter set overhead.

rise at the right and connect with the input of the set on the upper left-hand panel. The first two vertical bays are the radio set proper, including the automatic gain control. The third bay, on the right, includes the volume indicator and control and the line connecting equipment.

In general, three wavelengths are used, one around 19,000 kc. (16 meters), one around 14,000 kc. (21 meters) and one around 9,000 kc. (33 meters), and each transmitter and receiver is arranged so that it can be connected at any time with a directive antenna designed for each of these frequency ranges. The transmitter antenna gains are about 17 db over a one-half wave antenna. These short-wave radiotelephone facilities which connect the American telephone network with Europe and South America have already been the subject of technical papers [3] and need not be described in further detail. An air view of the Lawrenceville, N. J., transmitting station is given in Fig. 5. The longer of the two lines of towers supports the antennas

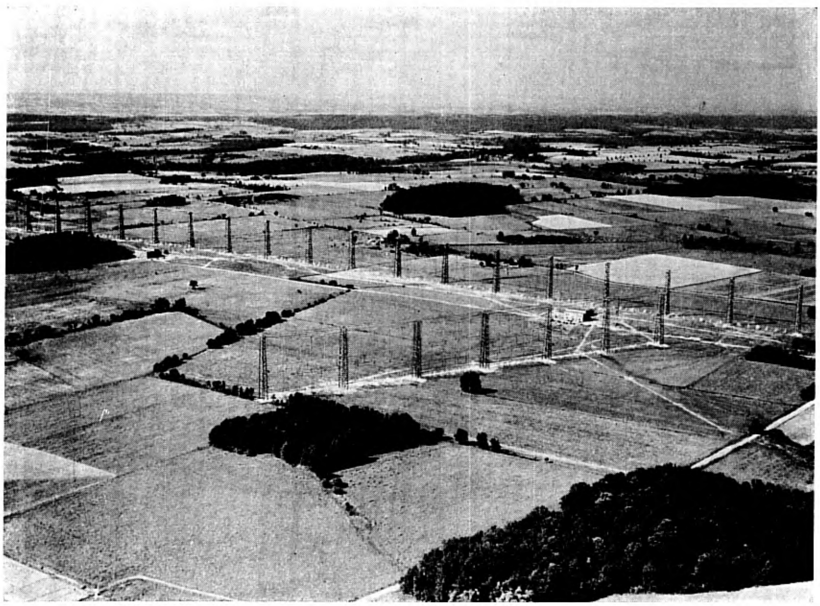

Fig. 5—Lawrenceville transmitting station. Aerial view—South American antenna in the foreground; European antenna in the background. Two buildings each containing two transmitters are shown.

for the three short-wave circuits to England, and the shorter line of towers the antennas for the single circuit to the Argentine. Some idea of the magnitude of the plants employed for these short-wave circuits may be had from this photograph. The longer line of antennas is approximately one mile long, consisting of twenty-one 185-ft. towers. Substantial fireproof buildings are provided for the transmitting sets and auxiliary equipment. Probably every operating agency which has

[3] See bibliography.

had experience with short-wave operation realizes that the cost of such radio facilities is proportional to the standard of service and to the degree of reliability and exactitude of operation which is undertaken in the terminal stations.

Joining of a Radiotelephone Link with Wire Network

The manner of joining the transoceanic radio links with the wire network to meet the requirements of through two-way transmission is an interesting and important development in itself. In general this technique is an outgrowth of wire telephone practice and is so new as not yet to have been fully applied to all of the radiotelephone links in existence.

The problem is that of how to form the two oppositely directed speech channels which comprise the radiotelephone link itself into the usual two-way telephone circuit suitable for use as a regular telephone toll line and for termination before long-distance traffic operators at each end.

The transmission equivalent of the radio paths may be continually changing over a considerable range due to fading. It is undesirable that noise or speech on the incoming channel be reradiated on the outgoing channel. Any tendency for the system to sing must be avoided. It must be possible to change the amplification looking into the transmitters over a wide range so as to get a fully modulated output from them, irrespective of the length of the connected lines or the volumes of the talkers' voices. Furthermore, in some cases, as where the same radio-frequency band is used for transmission in the two directions, the radio transmitter tends to interfere with the receiver at the same end.

A solution of these conflicting requirements necessitates that only one of the radio paths be connected to the wire network at a time. This fundamental principle at one stroke wipes out singing, reradiation or echoes, and permits independent adjustments of amplification in the two radio paths. To apply it, it becomes necessary to employ voice-current-operated switching devices which connect alternately the sending or receiving radio channel to the wire line as the subscriber talks or listens, automatically following the conversation and serving the needs of the subscriber without his volition.

Various mechanisms for carrying out this function have been devised. Some employ mechanical relays for switching while others use vacuum tubes, but in principle they are much alike. The broader ideas involved are illustrated in Fig. 6. When the circuit is quiescent, i.e., neither subscriber speaking, the receiving radio channel is connected and the transmitter disconnected. Speech coming from the wire line connects the transmitter and disconnects the receiver. The positive switching action is, therefore, dependent upon the impulses of speech from the land line. This arrangement is preferred to the reverse one of depending upon impulses of speech receiver over the radio channel. This is because the system must operate on speech only and not noise, and the speech-to-noise-ratio is usually higher and more dependable on the wire line than on the incoming radio channel.

This single function of switching-over in response to the subscriber's voice is the principal and basic function of such devices. There are, however, many auxiliary features incorporated to guard against false

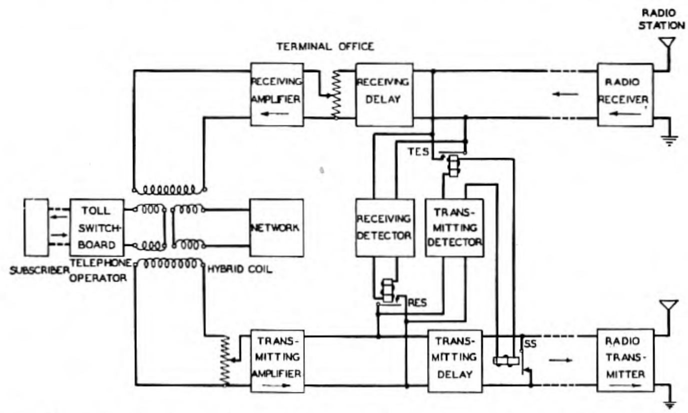

Fig. 6—Circuit diagram illustrating operation of voice-operated switching device, Note: Voice currents coming from the line, rectified in the transmitting detector. clear the transmitting path by removing short circuit at *SS* and short-circuiting receiving path at *TES*. Switch at *RES* is operated by received radio speech or noise to prevent echoes in the wire lines from reaching transmitting detector.

operation by noise currents and speech current echoes which greatly increase the ability of the arrangement to operate satisfactorily under conditions of severe noise or weak speech. These have been described elsewhere [4] more completely than would be appropriate in this discussion.

Viewed from the radio standpoint these voice-operated devices are of great importance since they permit radio links to be used as trunks in wire networks without their having to meet the requirements which wire line trunks must meet. At the present stage of development it would be practically impossible to provide radio circuits meeting wire line standards.

[4] See bibliography 7.

Transmission Results

We now come to a consideration of these transoceanic links which is perhaps the most important one from the standpoint of the service given and of the engineering development required. It is that of the general transmission effectiveness and of the continuity of service which is given. So far as the radiotelephone circuits operating out of the United States are concerned, this phase of the subject is pretty well summarized by the charts given in Fig. 7. These show from top to bottom the continuity of *two-way transmission* which has been obtained over the past year, (1) on the long-wave transatlantic circuit, (2) on one of the short-wave transatlantic circuits, and (3) on the short-wave circuit which operates with Buenos Aires. The last named circuit has been in operation only since the spring of this year.

The black areas show in each case the hours of the day during which the circuit was commercially usable. The white gaps indicate periods during which no operation was attempted and for which there are no data. The dotted-in lines show the periods during which the circuit was found to be commercially unusable, i.e., the lost time periods.

The following points are to be noted:

1. The long-wave circuit, shown at the top, is poorest during the summer months. This is because of atmospheric disturbances due to lightning. Throughout the year shown, the long-wave circuit was available for service about 80 per cent of the time
2. The North Atlantic short-wave circuit, center figure, was fairly good last summer but suffered much lost time during the spring months of 1930. The poor behavior during the spring is apparently due to unusually high solar activity. Such related phenomena as aurora disturbances in the earth's magnetic field, and earth currents have been affected similarly. For the year shown this short-wave circuit was commercially available about 64 per cent of the operating time. Similar experience was had on the other two transatlantic short-wave telephone circuits, one of which was operated over a longer period of the day than that shown.
3. The combination of the North Atlantic of the long-wave and short-wave circuits gives a much improved result as compared with either one alone. As is indicated in the diagrams, last summer when the long wave circuits suffered from "static," the short-wave transmission was fairly good; conversely, this last winter and spring when the short-wave transmission suffered severely from magnetic storm effects, the long-wave circuit was the mainstay of the service.

4. The short-wave transmission between New York and Buenos Aires, as depicted by the bottom chart of Fig. 3, will be seen

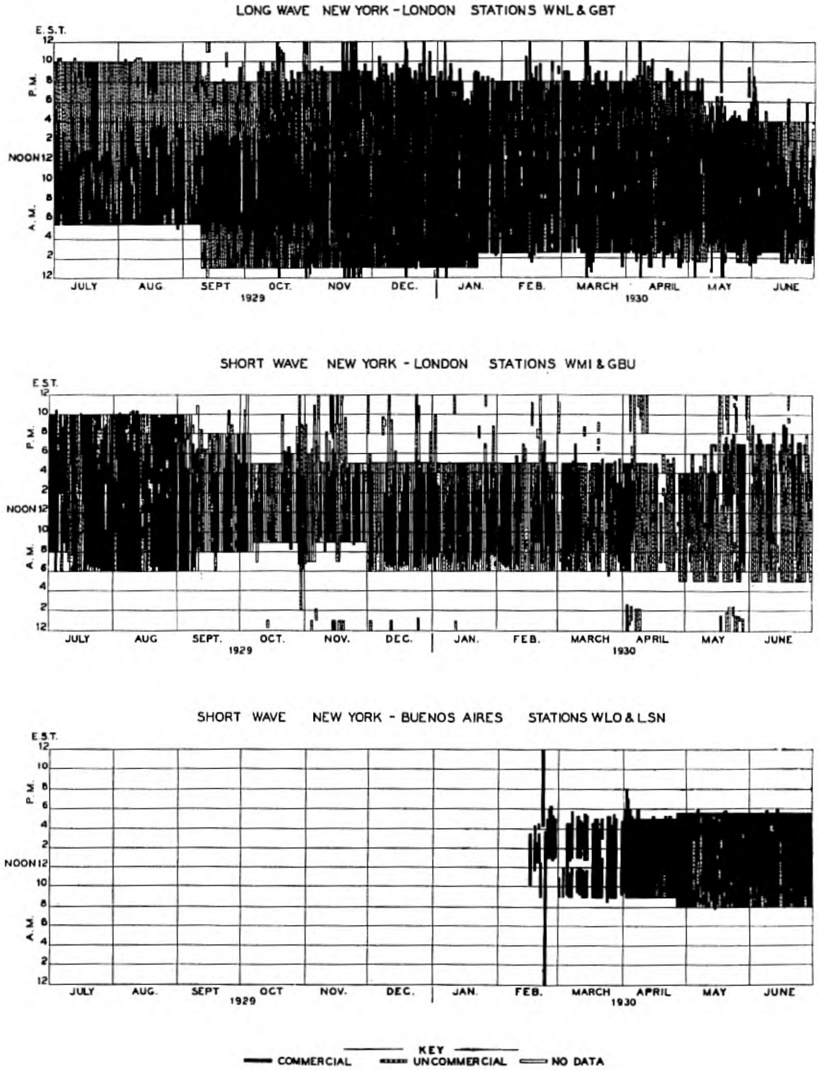

Fig. 7—Chart showing transmission results on long waves—transatlantic; short waves—transatlantic; short waves—South America.

to be more reliable than short-wave transmission across the North Atlantic. The single short-wave circuit between New York and Buenos Aires has, since the initiation of this service last spring, been commercially usable about 97 per cent of the operating time.

The difference in short-wave transmission east and west across the North Atlantic and that across the tropical zone, shown in Fig. 7, is quite in keeping with the general experience of other operating agencies and is already a well recognized fact in short-wave transmission. There is obviously a radical difference in the character of the transmission paths involved which requires further survey and analysis.

Typical Magnetic Storm Effect

It will be noted from the second diagram of Fig. 7 that the interruption of short-wave transmission across the North Atlantic sometimes continues for several days at a time. These periods have been found to correspond to disturbances in the magnetic state of the earth and to be accompanied by the appearance of relatively large differences of electric potential along the earth's surface. Measurements which have been carried out on the strength of electric field received across the Atlantic during such periods and simultaneous records which have been made of earth potentials shed some light on what happens during these periods.

There is shown in Fig. 8 observations which were made during a major effect of this kind which occurred in July, 1928. Short-wave transmission conditions appeared to have been normal both before and after the occurrence of this effect. The measurements were made at New Southgate, England, upon station WND, one of the radio transmitters at Deal, N. J., used before the present transmitting plant at Lawrenceville was built. The measurements were made on 18,340 kc. during the normal hours of daylight operation. The upper curve of the figure shows the variation in received field strength averaged over the daylight hours for each of the several days shown. Below the field strength curve there is plotted a record which was made during this same period of the earth potentials in the vicinity of New York. This is a smoothed transcript of a record taken on a continuously operated recorder connected in a grounded wire circuit which extended from New York westward to Reading, Pa., about 100 miles distant.

It will be observed that the time of minimum field strength coincided approximately with the time of maximum earth potential (the small wiggles of earth potential are to be neglected since they are due to disturbances set up by man-made electrical systems). The drop in the strength of the received field will be observed to be large, of the order 35 db. The effect upon transmission lasted several days, the recovery appearing to have been slower than the initial effect.

A high degree of coincidence has been found to exist between these adverse effects in short-wave transmission on the one hand, and on the other hand the appearance of earth currents and abnormalities in the earth's magnetic field. This is a subject which cannot be adequately treated in the present paper and it is hoped that a report upon it can be made to the Institute during the forthcoming winter. As is explained below radio transmission is believed to be largely dependent

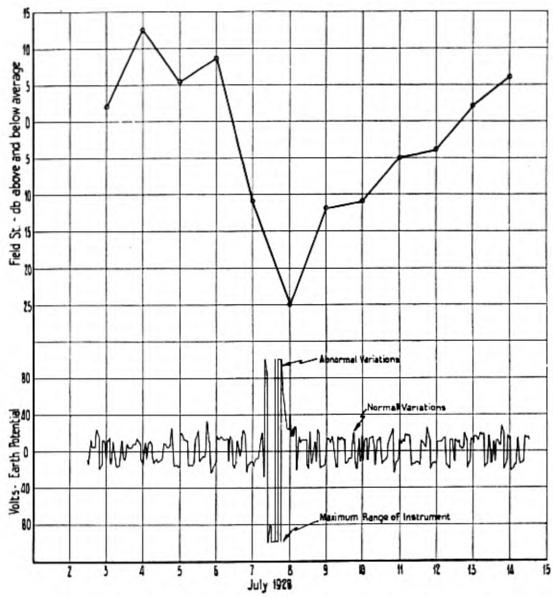

Fig. 8—Magnetic storm effects, showing drop in field strength and appearance of earth potentials.

on the state of ionization of the earth's atmosphere. Earth potentials are probably also affected by variation in this ionic state. Therefore, we have in such a recorder a useful check on the transmitting medium when transmission difficulties are encountered. Such earth potential observations may prove to be useful in exploring these conditions more generally throughout the world.

In Fig. 8 each point of the radio data was obtained by averaging the field strength of the carrier throughout a 24-hour period. Fig. 9, on the other hand, presents in a more detailed manner the way in which the field strength varied throughout each of seven days, between June 24 and July 1, 1930, on transmission from England to the

U. S. A. Within this period, there was a magnetic storm. No data were obtained on June 29. The original curves were obtained with an automatic recorder, receiving from station GBU of the British General Post Office during regular operation. In redrafting for pub-

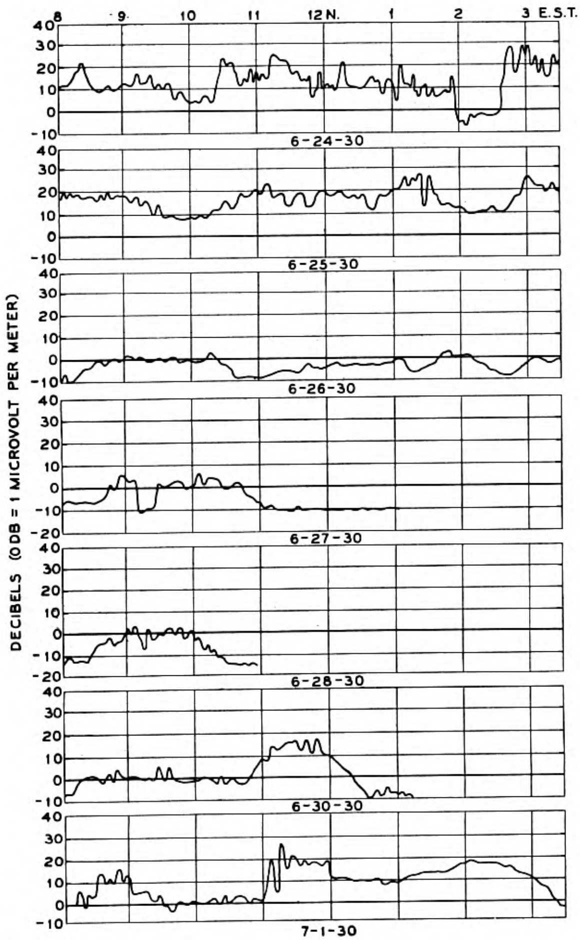

Fig. 9—Magnetic storm effect, oscillograms of received carrier.

lication, the rapid variations which are characteristic of fading have been eliminated and only the slow drifts are shown. It will be seen that the effect of the storm became evident on June 26, the average signal being 15 to 20 db lower than the preceding day. This condition continued on the 27th and 28th, on the 30th the signal averaged a little higher, and on July 1 a recovery had set in. The incompleteness of the record on three days is caused by the transmitting station shifting to a different frequency in an attempt to improve conditions. As to commercial transmission results over this channel during this period: the first two days were fair, the third day poor, the 27th, the 28th, 29th, and 30th very poor, and July 1 still rather poor.

The Problem of the Transmitting Medium

These adverse effects in short-wave transmission are ascribed to the nature of the medium through which the propagation of the waves takes place. The short-wave signals which reach a distant point are carried by waves which have traveled in the upper regions of the atmosphere, where a condition of ionization exists which causes the waves to move in a curved path and, finally, to arrive again at the earth's surface. The ionization in the upper part of the atmosphere varies with atmospheric conditions and hence its action on the waves which are passing through it varies from day to night, from season to season, in a more or less regular manner, on which are superposed fortuitous variations due to other conditions. The conditions in the upper atmosphere may be such that two or more waves arrive at a distant point from the same source after having traversed different paths. If the length of one of the paths is changing, the resulting signal from the two waves will pass through a series of maxima and minima in time, which process is known as fading. This complicated path condition is present at practically all times, since it is only on very rare occasions that short-wave signals do not fade in and out. Furthermore, there appear to be different kinds of fading corresponding to different transmission paths. For example, the fading on the North Atlantic short-wave circuits is of a deep slow variety as compared with the faster and more choppy type of fading experienced on the north and south circuit between New York and Buenos Aires.

To some extent this fading can be overcome by means of automatic gain control in the radio receiver which causes a steady signal to be delivered to the listener. However, this does not correct for the distortion which may be produced by interference between two transmission components. This distortion may result from a selective fading of the various frequencies in the voice band and an oscillogram showing this condition is given in Fig. 10 which is taken from a paper by R. K. Potter.[5] These are records of transmission across the North Atlantic of the voice band occupied by 10 suitably spaced tones of equal amplitude at the transmitting end. There is shown in the vertical columns a succession of snapshots which are separated

[5] See bibliography 19.

by intervals of about one-twelfth of a second. By following these columns down, the progressive change which occurs in the distortion of the voice band may readily be seen. The worst distortion occurs at

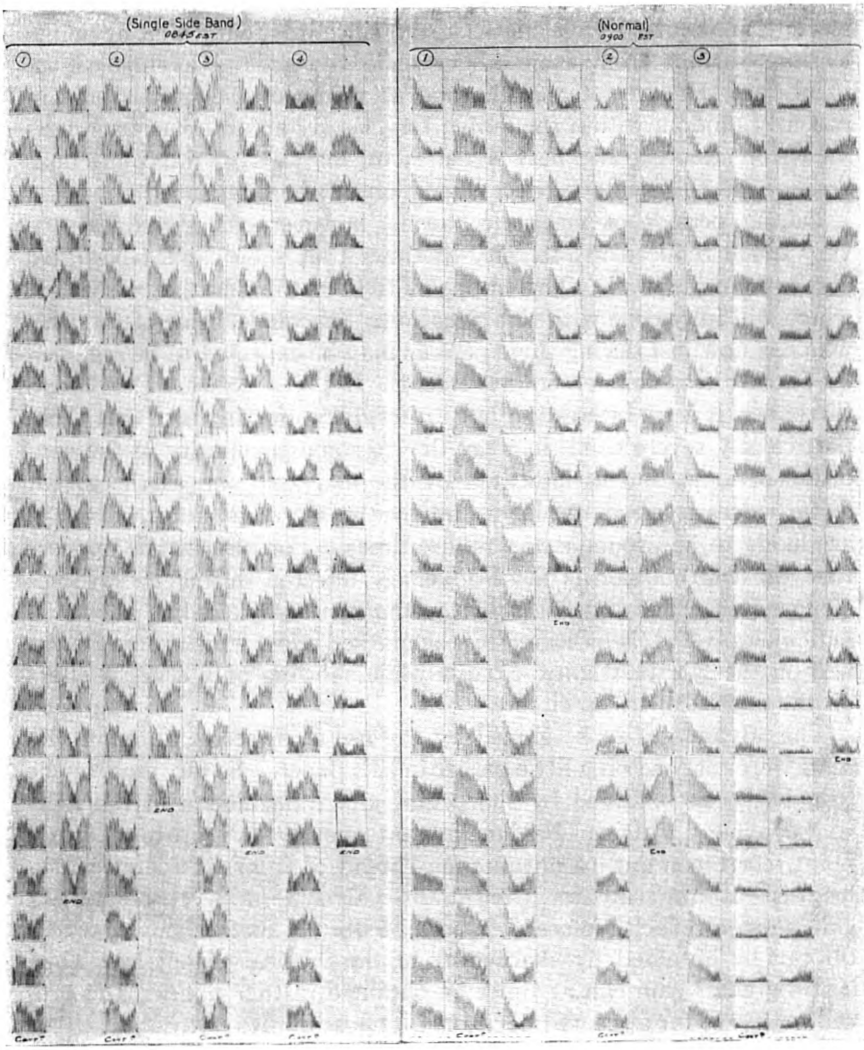

Fig. 10—Distortion of voice band in short-wave transmission.

times when the carrier itself is blotted out. Tests have indicated that the use of single side band is of value in minimizing this type of distortion. Experiments have been in progress for some time looking to the evaluation of gain to be expected along these lines from the introduction of a single side-band system and toward the development of single side-band equipment for use at these frequencies.

Another method which might be employed to reduce this type of distortion is to pick up the signal on a number of antennas spaced more than about 10 wavelengths apart, since it is found that at points this far distant from each other, while the general average signal values are the same, the instantaneous values of the signals are apparently random within the fading limits. By an automatic arrangement for selecting the best signal from, let us say, three antennas arranged in this manner, voice distortion can be diminished.

During periods of magnetic storms, however, the signals are so very much reduced in intensity at times that they cannot be heard above the noise level. There appears to be nothing in the present art which will fully cope with this situation. Of course, some of the time which is now lost during these periods may be expected to be regained by further transmission improvements. As was indicated earlier in the paper, it is an interesting but rather discomforting fact that these particularly severe conditions are due to some peculiarity in the condition of ionization as indicated by the magnetic and earth current disturbances referred to above and by the fact that aurora displays are likely to be pronounced at these times. Furthermore, it appears that the transmission is most adversely affected during these times along paths which pass near the aurora zones surrounding the magnetic poles. This is indicated by the marked effect which these storms had on the North Atlantic circuits while showing only a slight effect on the South American circuit.

The advantages to be gained by the use of directive antenna systems were touched on a little earlier in this paper. So far, most of the gain has been obtained by sharpening the transmission in the horizontal plane. This can be done advantageously only up to a certain point, corresponding to an antenna spread of from six to ten wavelengths—at any rate for transatlantic signals—and representing a gain when a reflector is used of about 15 db. A further gain of 3 to 5 db can be obtained by sharpening in the vertical plane; and while a still greater gain can at times be obtained in this manner, the procedure has so far appeared not worth its possibilities of trouble. This is due to the fact that with varying conditions in the upper atmosphere, the waves as they reach the receiving station apparently approach from different vertical angles and care must be taken not to build an antenna with such a sharp vertical characteristic that the received waves will fall on the antenna at such an angle that its calculated gain cannot be realized. We have, in fact, constructed several antennas sharp in the vertical plane, which have given as much as 16 to 20 db gain over a one half wave vertical antenna on local test but which have given for a signal from a distant point all variations of gain from this same value down to a loss of 2 db.

Planning the International Use of Frequencies

The problems of the transmitting medium discussed above are those which have been under study in connection with telephone transmission across the North Atlantic and between North and South America. Doubtless further observation and the exploration of other portions of the earth's surface will disclose a much more complete picture than it is now possible to present. It is important that further data be gathered not alone for the purpose of improving the transmission results obtained but also for use in agreeing internationally upon the most effective use of the frequency spectrum for different services in the interest of the world as a whole.

Of fundamental importance is the question of the frequencies which are best suited to different distances of transmission. The curves of Fig. 11 [6] give this relationship between frequency and distance in so far as it has been disclosed by measurements carried on between North America and Europe and South America, and also between the American continent and ships plying the Atlantic Ocean. In the construction of these curves use has been made also of data obtained by other agencies such as the Radio Corporation and the United States Navy Department. The curves are reproduced here merely for such use as they may be in connection with this problem of planning and with the hope of stimulating the contribution of corresponding data for other regions of the earth. It should be realized that actually each curve is the center of a considerable band of frequencies and that these bands merge one with another.

While experience has indicated that during the adverse transmission conditions which accompany a magnetic storm some improvement in transmission can at times be obtained by shifting the frequency. In general, these effects are found to extend over the entire high-frequency range now in general use, and shifting frequency does not dodge them.

In view of the extent to which transoceanic radio links, telegraph as well as telephone, are dependent upon the use of the higher frequencies, and of the importance of communications to the world as a whole, it is highly desirable that they be conserved for these longer distance uses. This has already gained recognition and the 1929

[6] See bibliography 22.

Hague Conference of the C.C.I.R. has recommended it as a principle. The carrying of it out in practice means that, in general, communications over the shorter distances should be carried out on the lower of the high frequencies (and possibly at the extreme high frequencies). It logically calls, also, for making the maximum use of existing wire networks for overland services, in order to free the radio channels for uses for which they are most needed. Finally, there is, of course, the need for coordinating the transoceanic links among themselves and minimizing unnecessary duplication.

In the Washington, 1927, Convention the world took a constructive step forward in organizing the use of radio channels by blocking out the high-frequency spectrum in respect to classes of service, thus:

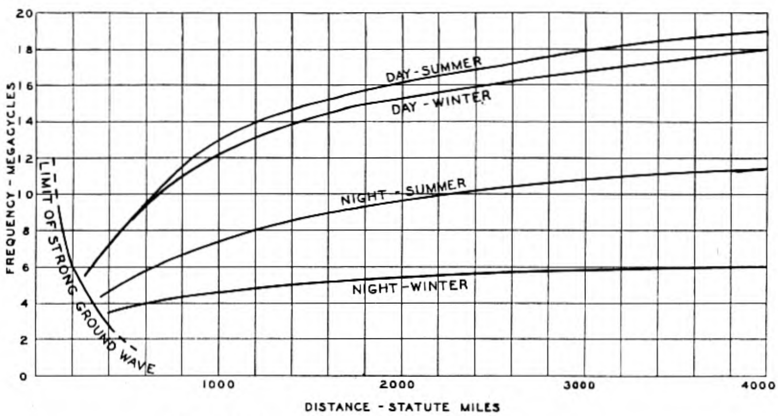

Fig. 11—Frequency-distance characteristic.

point-to-point, relay broadcast, mobile services. It is of interest to note that there is a further line of distinction which might be availed of for the purpose of reducing interference. As matters now stand, powerful and expensive stations which can well afford to live up to the highest standard of frequency stability, radio receiver selectivity, etc., are intermixed in the frequency spectrum with stations which cannot justify living up to these standards. Wide differences, in the caliber of station in accordance with the different needs is, of course, to be expected. This would appear to call for some grouping of stations in the various frequency bands in accordance with the frequency tolerance which they are prepared to meet. Some indication of the prevalence of interference on these short waves is given by the experience which has been had in operating the transatlantic short-wave telephone circuits during the first six months of 1930. Of some 3,000 operating hours in which the short-wave circuits were commercially useful, 110 hours, or about 3 per cent of the time, were lost due to interference from other stations. The frequencies of the interfering stations were found to differ from their registered frequencies by varying amounts up to hundreds of kilocycles.

The Hague 1929 Conference of the C.C.I.R. recommended that the frequencies of fixed stations operating in the 6,000 to 23,000-kc. range be held to 0.05 per cent tolerance and improved to 0.01 per cent as soon as possible. That this is not an unreasonable requirement for large stations is indicated by the following results of measurements made on the four short-wave telephone transmitters at Lawrenceville, N. J., during the periods of regular operation for the first half of 1930. Of 2826 measurements of the frequencies of these transmitters which were made at a measuring bureau 99.75 per cent were within the ± 0.05 per cent deviation, and 89.1 per cent were within the ± 0.01 per cent.

The existence of the problems of the transmitting medium and of the reduction of interference is a reminder of the need which exists for further quantitative studies of radio transmission throughout the world and of radio station performance, in the interest of the more effective use of the radio channels of the world.

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Some Optical Features in Two-Way Television *

By HERBERT E. IVES

A comprehensive description of the two-way television system now being demonstrated between the American Telephone and Telegraph Company building, and the Bell Telephone Laboratories, in New York City, has been published elsewhere.[1] Part of that account gives the essential features of the optical arrangements whereby the users of the apparatus are appropriately lighted, and are assured against visual discomfort from the scanning operation. Since the apparatus was first installed, however, some important changes have been made in the distinctively optical features, whereby the performance of the system has been notably improved, and its operation considerably simplified. These changes deserve description, and the present account is mainly concerned with them, although for the sake of completeness some details previously described are included.

IT IS an inherent feature of the two-way television system that either user is continuously scanned as he views the image from the distant station. The beam scanning method,[2] by which a beam of light sweeps over the subject's face, enables the scanning operation to be performed with a minimum amount of light. Even so, because of the relatively low intensity of the television image, it is necessary to reduce the intensity of the scanning beam in every way possible. In the two-way apparatus as first operated, advantage was taken of the fact that the photoelectric cells employed, which were of potassium, were principally sensitive to blue light. The scanning beam derived from a high power arc lamp was accordingly passed through a deep blue filter, which reduced the photoelectric efficiency of the beam very little, but because of the relatively low visual value of blue light, effectively reduced the brightness of the beam many times. The user of the apparatus saw, above the incoming image, merely a mild blue spot of light, which did not interfere with his vision.

A disadvantage of the use of blue light, which was anticipated, and found in practice to be quite real, was that dark, tanned, or ruddy complexions were rendered as altogether too dark, in comparison with whites such as the ordinary linen collar. The effect is precisely that encountered in the earlier photographic processes before color sensitive plates and color filters were available. While this defect was minimized by the use of a dark background, and to some extent by chopping off the highlights by electrical means, it was recognized as undesirable.

* *Jour. Optical Soc.*, Feb. 1931.

[1] *Bell Sys. Tech. Jour.*, July 1930.

[2] *Jour. Optical Soc.*, March 1928.

One recent improvement in the apparatus is a change in the nature of the scanning light, whereby, without sacrificing the general principle of using visually inefficient but photoelectrically efficient radiation, the proper balance of tone values in the face is restored. This has been accomplished by adding to the battery of blue sensitive potassium cells, a group of red sensitive cæsium oxide cells, and scanning by *purple* instead of blue light, that is, both ends of the visible spectrum are used in place of one end.

In making this change, a number of others were involved, most of which resulted in simplification or improvement. One important alteration was the substitution for the arc lamps previously employed, of incandescent lamps of a type available from motion picture projection practice, as shown in Fig. 1. The lamp employed has for its radiator, four vertical helical coils of tungsten wire, and is furnished with a reflector which images the coils back on the intervening spaces. An efficient condenser system throws a brilliant rectangular image on the back of the scanning disc, which is substantially uniform over the whole field. With this unit, the scanning beam as it leaves the projection lens is somewhat larger in diameter than the beam as produced from the arc. Consequently, for positions away from the focused image of the disc holes, the scanning beam is larger than before, with some resultant loss in the range of sharpest definition. Since, however, the user of the two-way apparatus is seated in a fixed chair, he has little opportunity to move far out of the plane in which the disc holes are focused, so that this objection is not serious. The advantages of this substitution were two-fold. First was a great gain in simplicity of operation and maintenance. Second, the incandescent lamp, being a lower temperature radiator, radiates relatively many times as much red light as does the arc, for the same amount of blue. Consequently, once an incandescent lamp unit was found which gave the amount of blue light required for the potassium cells, the great excess of red light made possible the use of relatively few cæsium oxide cells. Since these are intrinsically somewhat more sensitive than the potassium cells, the net result was that a red signal comparable with the blue signal could be added by the installation of only two cæsium cells, each of less than half the electrode area of the potassium cells.

It was found most convenient to mount the two cæsium oxide cells directly in front of the observer, to either side of the microphone, and above the opening in the booth through which the scanning beam enters, and through which the incoming image is seen. This arrangement is shown in Fig. 2. The only objection to placing the cells in this position is that they encroach somewhat into the region where reflections of the cells (which are virtual light sources) are likely to be seen reflected in eyeglasses. Since, however, the head is normally directed somewhat downward, cells placed in these upper corner spaces are not serious offenders in this respect.

Two other features of the two-way system which needed revision when the cæsium cells were adopted, were the variable angle prisms used to direct the scanning beam upward or downward, depending on

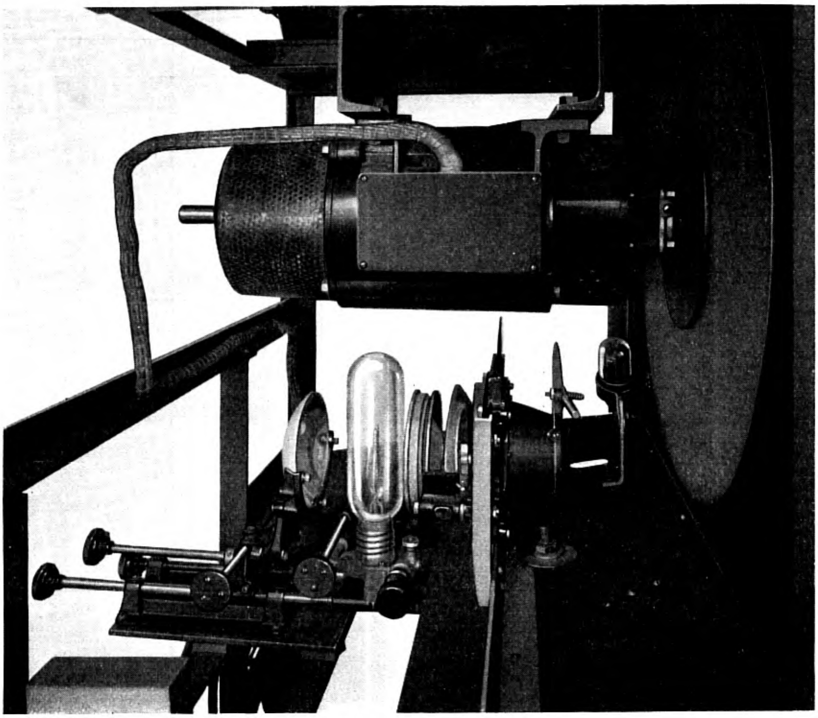


Fig. 1—Incandescent lamp used for scanning light.

the user's height, and the general illumination of the television-telephone booth. As to the variable angle prisms, the only change called for was the substitution of achromatic prisms, corrected for deep red and blue light, in order to prevent the scanning beam from breaking effectively into two beams for large angles of deviation. The problem of general illumination of the booth is principally the choice of a color of light which shall affect neither the potassium nor the cæsium cells. For this purpose, a monochromatic yellow-green was chosen, secured by covering all the lights with a combination of orange and signal green glasses. The potassium cells are insensitive to this color of light, and the cæsium cells were rendered so by placing over them, windows covered with a deep purple gelatin. This choice of illumination color made possible a satisfactory general level of illumination of the booth and the surroundings of the image without introducing spurious signals.

The transmissions of the purple filters, the response curves of the potassium and cæsium oxide cells, the radiation curve of the incandescent lamps used for the scanning beam, and the transmission curves of the glasses used over the lamps for general illumination, are shown

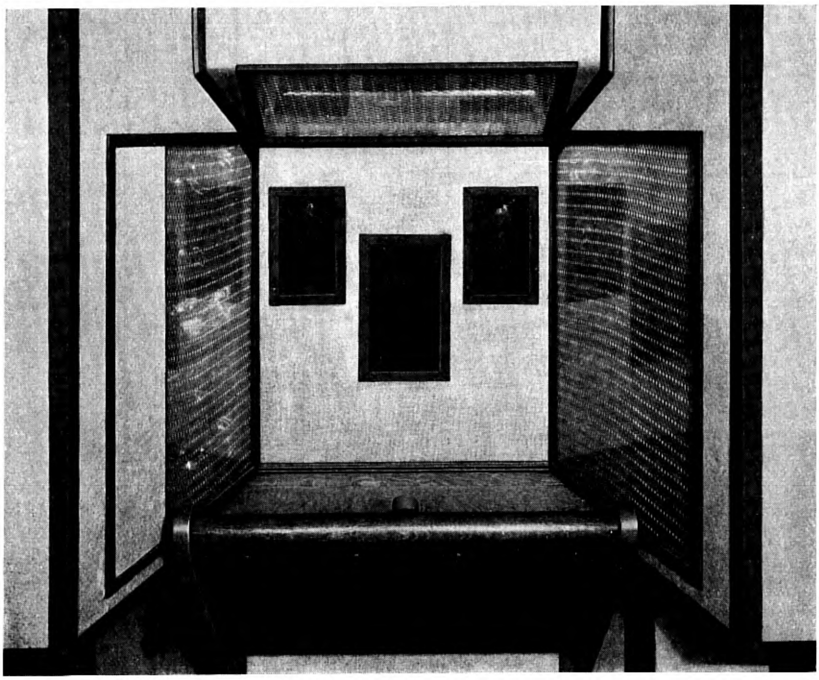


Fig. 2—Interior of two-way television booth showing location of two cæsium cells above and to either side of scanning and viewing aperture.

in Fig. 3. Comparing these with the response curve of the eye, also shown in the same figure, it will be evident how the general problem of securing photoelectric signals of maximum efficiency without interfering with the general quality of the image, or desirable conditions of illumination, has been secured.

Before going on to describe some of the optical features at the receiving end, we may pause to discuss the improvements in the television signal which have been introduced by the changes just described. There is, of course, a substantial gain in the steadiness of the image due

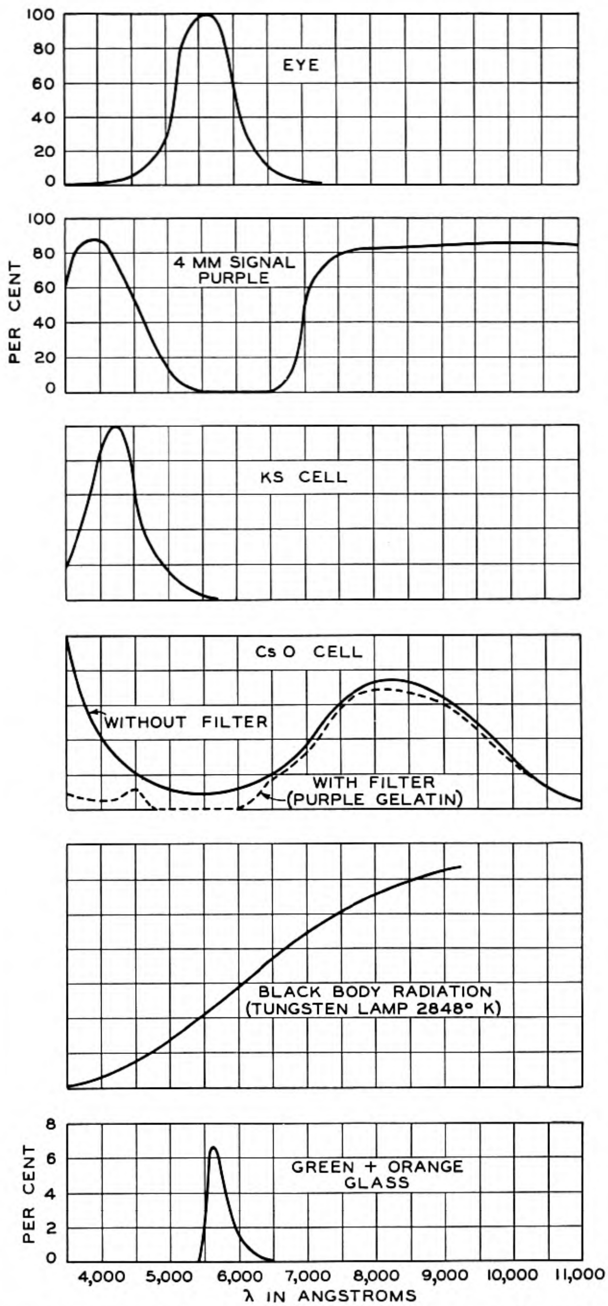


Fig. 3—Spectral characteristics of the scanning, viewing and illumination elements in two-way television system.

to the elimination of the arc lamps, much of whose effective radiation was from the arc stream which always wanders somewhat. The chief gain, however, is in the tone quality of the image of the face. The difference is very clearly shown if shutters are arranged so that either the potassium or the cæsium cells may be used alone, alternately, and can then be quickly exposed together. With the potassium cells alone, as already noted, flesh tints are in general too dark, and tanned or ruddy complexions show unnatural contrast with the whites. Highlights due to reflection on the skin are often observed to be out of scale, with a resultant effect of mottling of the skin. With the cæsium cells alone, on the other hand, the flesh tints are in general too light, and faces are apt to appear very flat. These differences were anticipated, but others not so obviously to be expected, have been observed. For instance, with the cæsium cells, the pupil and iris of the eye are brought out with rather startling blackness, while with the potassium cells, the detail around the eyes is apt to be lost. The most satisfactory results are obtained with both sets of cells acting, for, as was hoped, the combination of the two ends of the spectrum, gives, in the case of the face, an effect very like that which light from the middle of the visible spectrum would give, that is, an "orthochromatic" image, as it would be described in photography, while the definition of important points, such as the eyes, is distinctly improved.

Passing now to the receiving end of the two-way television apparatus we recall that in the apparatus as originally set up and described, a simple disc with a spiral of holes was used, immediately behind which was a neon lamp with a large flat water-cooled electrode. On continued operation, it was found that the heavy current demanded in these lamps, in order to secure an image of sufficient brightness, caused rapid sputtering on the closely adjacent glass wall, necessitating frequent renewals of lamps. A very radical change in the disc and lamp design has been made by which this undesirable situation has been remedied.

The change in the disc consists in substituting for the simple Nipkow disc, with its spiral of holes, an alternative form, suggested also by Nipkow, in which each disc hole has associated with it a condensing lens, positioned so as to focus, in combination with a fixed collimating lens, and image of the source on the disc hole. The optical arrangement is shown in Fig. 4, and a photograph of the disc with lenses and lamp in place in Fig. 5. Referring to Fig. 4, D represents in section the simple disc with a spiral of holes, h; l represents a small short focus lens, fixed in position with respect to h at a distance equal to its focal length; L represents a fixed lens of diameter large enough to cover the

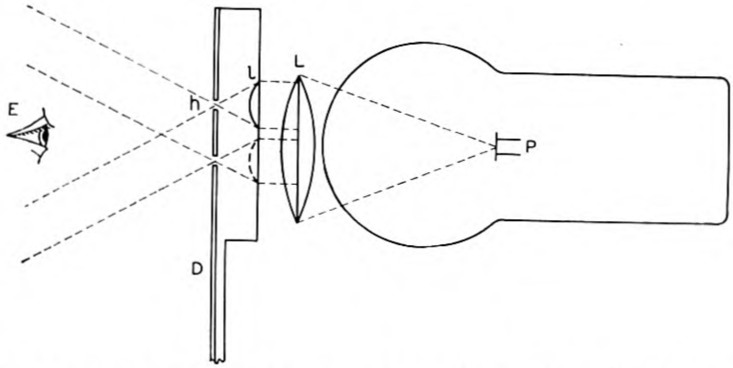


Fig. 4—Section of disc with lens system for utilizing small area light source.

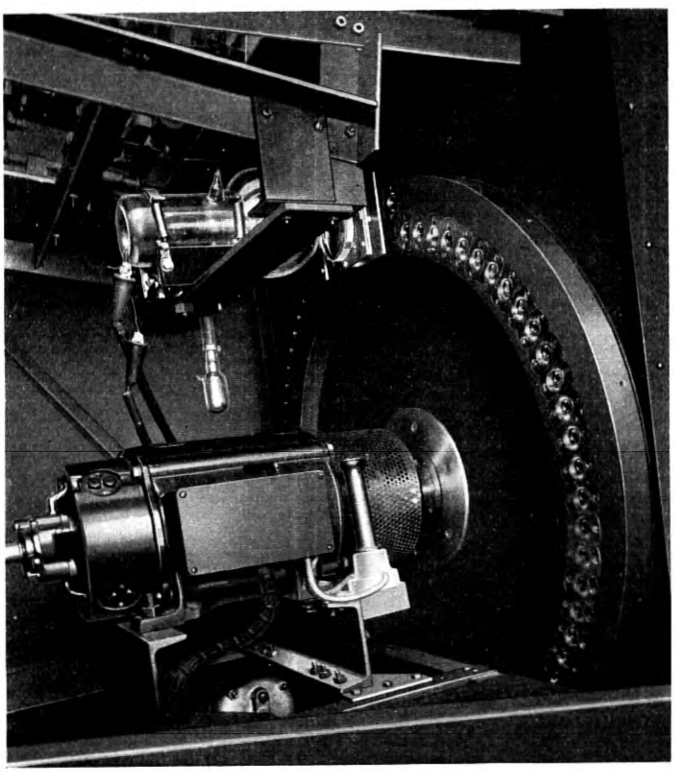


Fig. 5—Disc with condensing lenses as used at the receiving ends of two-way television system.

entire frame of the picture and the lenses l; P represents the glow lamp electrode. A great advantage of this optical arrangement is that the cathode of the glow lamp can be made quite small, and can be removed, as shown, to a considerable distance from the glass wall of the containing tube. In consequence of these changes in lamp design, a very high current density can be obtained for a relatively low expenditure of energy, with at the same time a long lamp life.

The condenser lens disc is observed exactly as the simple disc, by the eye placed at E. According to Nipkow, when lenses are used on the disc, the holes should be covered with diffusing material. This is not necessary in the present case, because in the two-way booth, the observer has very little latitude of motion, and it is only necessary that his eyes lie in the overlapping cones of rays from the extreme holes in the field. By making the lenses l of large diameter compared with their focal length, the solid angle through which an image is visible is entirely adequate.

The general characteristics of the lamps used are shown in Figs. 4 and 5. The cathode is a heavy slug of copper, into which a hollow cylindrical aluminium electrode is screwed, shielded from the copper by mica and glass. Because of the large mass of the copper, the water-cooling is no longer necessary. With lamps of this type, the amplifier circuit used before makes it possible to obtain images of much greater brilliancy, whereby the contrast between the image and the scanning light is still further increased beyond what was before found satisfactory. This margin of brightness is so large that it has been found possible to use lamps filled with helium in place of neon, giving a much whiter image, more pleasing to some people.

Bayes' Theorem

An Expository Presentation *

By EDWARD C. MOLINA

BAYES' theorem made its appearance as the ninth proposition in an essay which occupies pages 370 to 418 of the Philosophical Transactions, Vol. 53, for 1763. An introductory letter written by Richard Price, "Theologian, Statistician, Actuary and Political Writer," [1] begins thus:

> "I now send you an essay which I have found amongst the papers of our deceased friend Mr. Bayes, and which, in my opinion, has great merit, and well deserves to be preserved."

A few lines farther on Price says:

> "In an introduction which he has writ to this Essay, he says, that his design at first in thinking on the subject of it was, to find out a method by which we might judge concerning the probability that an event has to happen, in given circumstances, upon supposition that we know nothing concerning it but that, under the same circumstances, it has happened a certain number of times, and failed a certain other number of times."
>
> . . . .
>
> "Every judicious person will be sensible that the problem now mentioned is by no means merely a curious speculation in the doctrine of chances, but necessary to be solved in order to a sure foundation for all our reasonings concerning past facts, and what is likely to be hereafter."

No one will dispute the importance ascribed to Bayes' problem by Price; in fact, a paper by Karl Pearson on an extension of Bayes' problem is entitled "The Fundamental Problem of Practical Statistics." Opinions differ, however, as to the validity and significance of the solution submitted in the essay for the problem in question. In view of this situation I shall limit myself today to an exposition of the fundamental characteristics of the problem Bayes' theorem deals with and shall give no consideration to its interesting applications.

The exposition may be outlined as follows: after specifying the class of problems to which Bayes' theorem pertains I shall:

* Read before the American Statistical Association during the meeting of the American Association for the Advancement of Science in Cleveland, Ohio, December, 1930.

[1] These titles are associated with the name of Price in the frontispiece portrait of him bound with the December, 1928, issue of *Biometrika.*

I. Discuss briefly two problems each of which will emphasize one of two kinds of *a priori* probabilities which should be constantly borne in mind when Bayes' theorem is under consideration,

II. Partially analyze a certain ball-drawing problem which will not only serve as an introduction to the algebra of Bayes' theorem but will later help to throw light on its significance,

III. Present Bayes' problem and the related theorem,

IV. Make some remarks on the value of the theorem and the controversies which it raised.

In carrying out this plan I shall find it convenient to ignore the historic order of events.

When probability is the subject under consideration one anticipates problems such as: A coin is about to be tossed 15 times; what is the probability that heads will turn up seven times? A sample of 100 screwdrivers is to be taken from a case containing 1000 screwdrivers of which 300 are known to be defective; what is the probability that the sample will contain 25 defectives?

These are direct, or *a priori*, probability problems. In each of them the nature of a game, or an experiment, is specified in advance and then a question is asked relating to one, or more, of the possible outcomes of the game or experiment. Problems of this type have occupied the attention of mathematicians since the days of Pascal and Fermat, the creators of the mathematical theory of probability.

An inverse class of problems of great practical significance, called *a posteriori* probability problems, came into prominence with the publication of Bayes' essay. In these we find specified the result or outcome of a game which has been played, whereas the question then asked is whether the game actually played was one or some other of several possible games. This type of problems is usually stated as follows:

> "An event has happened which must have arisen from some one of a given number of causes: required the probability of the existence of each of the causes."

I

Consider this example: during his sophomore year Tom Smith played on both the baseball and football varsity teams; we have been informed that he broke his ankle in one of the games; what are the *a posteriori* probabilities in favor of baseball and football, respectively, as the baneful cause of the accident?

Evidently the answer depends on the number of baseball and football games played during their respective seasons and also on the likelihood of a man breaking an ankle in one or the other of these two games. As a concrete case assume that:

1. At Smith's college an equal number of baseball and football games are played per season;
2. Statistical records indicate that if a student participates in a baseball game the probability is 2/100 that he will break an ankle and that, likewise, the probability is 7/100 for the same contingency in a football game.

In view of the first of these two assumptions our conclusions as to the cause of the accident may be based entirely on the information contained in the second assumption. The odds are two to seven, so that the *a posteriori* probabilities regarding the two admissible causes are:

For baseball, $2/(2 + 7) = 2/9$.

For football, $7/(2 + 7) = 7/9$.

Now consider this other example. A lone diner amused himself between courses by spinning a coin. We elicited from the waiter that in 15 spins, heads turned up seven times. Moreover, from our point of observation, the size of the coin indicated that it was either a silver quarter or a ten-dollar gold piece. What are the *a posteriori* probabilities in favor of the silver quarter and the gold piece, respectively?

If the lone diner were a professor from one of our eastern universities we would not hesitate a moment in declaring that the coin spun was a quarter. But it happens that the gentleman was a member of the Cleveland Chamber of Commerce, dining at the Bankers' Club. We must, therefore, give the matter more careful consideration. The number of quarters and gold pieces usually carried by a banker and the probabilities of obtaining the observed result by spinning coins are relevant; let us assume, therefore, that:

1. The small change purse of a Cleveland financier contains, on the average, ten-dollar gold pieces and quarters in the ratio of eight to three.

Moreover, we may assume (in fact we know) that:

2. If either a quarter or a gold piece is spun 15 times, the probability that heads will turn up seven times is approximately 1/5.

The second of these two items of information makes the *a posteriori* probabilities depend entirely on the first item. Clearly the odds are eight to three and we conclude;

For a quarter, *a posteriori* probability $= 3/(3 + 8) = 3/11$.
For a goldpiece, *a posteriori* probability $= 8/(3 + 8) = 8/11$.

Now regarding the general *a posteriori* problem,

> "An event has happened which must have arisen from some one of a given number of causes: required the probability of the existence of each of the causes,"

what do the two examples we have just considered suggest? In both problems we inquired into:

1. The frequency with which each of the possible causes is met with BEFORE THE OBSERVED EVENT HAPPENED. This frequency is called the *a priori existence* probability for the corresponding cause.
2. The probability that a cause, if brought into play, would reproduce the observed event. This probability will hereafter be referred to as the *a priori productive* probability for the cause in question.

In the case of the broken ankle, the *a priori existence* probabilities were equal and took no part in our conclusion; we based the *a posteriori* probabilities entirely on the *a priori productive* probabilities. We did just the opposite with reference to the coin spun by the Cleveland financier; on account of the equality of the *a priori productive* probabilities we deduced *a posteriori* probabilities in terms of the unequal *a priori existence* probabilities.

It is apparent that our two examples represent extreme cases. In general, the solution of an inverse or *a posteriori* problem, involving a number of causes, one of which must have brought about a certain observed event, depends on both sets of direct, or *a priori* probabilities. Those of the first set give the frequency with which the various causes were to be expected before the observed result occurred; those of the second set give the frequencies with which the observed result would follow from the various causes if each were brought into play.

II

Bearing in mind the two distinctly different sets of *a priori* probabilities required in arriving at *a posteriori* conclusions regarding the possible causes of an observed event, we must now give some thought to the algebra of the subject before taking up Bayes' problem and theorem. For this purpose consider the following bag problem:

A bag contained M balls of which an unknown number were white. From this bag N balls were drawn and of these T turned out to be white. What light does this outcome of the drawings throw on the unknown ratio of the number of white balls to the total number of balls, M, in the bag? Let x be this unknown ratio.

Two cases of this problem may be considered:

Case 1.—After a ball was drawn it was replaced and the bag was shaken thoroughly before the next drawing was made;
Case 2.—A drawn ball was not replaced before the next drawing.

These two cases become essentially identical when the total number of balls in the bag is very large compared with the number drawn. Case 1 will serve as an introduction to Bayes' problem; later we will find it highly desirable to consider Case 2.

We are confronted with $(M + 1)$ possible hypotheses or causes before the drawings took place:

$$
\begin{aligned}
1 &- \text{the unknown value of } x \text{ is } x_0 = 0/M,\\
2 &- \text{the unknown value of } x \text{ is } x_1 = 1/M,\\
3 &- \text{the unknown value of } x \text{ is } x_2 = 2/M,\\
&\cdots\cdots\cdots\cdots\cdots\cdots\\
k + 1 &- \text{the unknown value of } x \text{ is } x_k = k/M,\\
&\cdots\cdots\cdots\cdots\cdots\cdots\\
M + 1 &- \text{the unknown value of } x \text{ is } x_M = M/M = 1.
\end{aligned}
$$

Let $w(x_k)$ be the *a priori* existence probability for the k'th hypothesis; by this is meant the probability in favor of the k'th hypothesis based on whatever information was available regarding the contents of the bag prior to the execution of the drawings.

Let $B(T, N, x_k)$ be the *a priori productive* probability for the k'th hypothesis; by this is meant the probability of obtaining the observed result (T whites in N drawings) when the value of x is k/M.

Then, the *a posteriori* probability, or probability after the observed event, in favor of the k'th hypothesis is

$$P_k = \frac{w(x_k)B(T, N, x_k)}{\sum_{k=0}^{M} w(x_k)B(T, N, x_k)}. \tag{1}$$

For Case 1 of our bag problem we have

$$B(T, N, x_k) = \binom{N}{T} x_k{}^T(1 - x_k)^{N-T},$$

where $\binom{N}{T}$ represents the number of combinations of N things

[2] This is the Laplacian generalization of Bayes' formula, although in some textbooks it is referred to as "Bayes' Theorem." A relatively short demonstration of it is given by Poincaré in his *Calcul des Probabilités*. See also Fry, *Probability and Its Engineering Uses*, Art. 49.

taken T at a time. Substituting in (1) we obtain, after canceling from numerator and denominator the common factor $\binom{N}{T}$,

$$P_k = \frac{w(x_k)x_k{}^T(1 - x_k)^{N-T}}{\sum_{k=0}^{M} w(x_k)x_k{}^T(1 - x_k)^{N-T}}. \tag{2}$$

If in equation (2) we give k successively the values a, $a + 1$, $a + 2$, $\cdots$ $b - 1$, b and add the results we have

$$P_a + P_{a+1} + \cdots + P_b$$

or

$$P(x_a, x_b) = \frac{\sum_{k=a}^{k=b} w(x_k)x_k{}^T(1 - x_k)^{N-T}}{\sum_{k=0}^{M} w(x_k)x_k{}^T(1 - x_k)^{N-T}} \tag{3}$$

for the *a posteriori* probability that the unknown ratio of white to total balls in the bag lies between a/M and b/M; both inclusive.

III

Bayes' Problem

Consider the table represented by the rectangle $ABCD$ in Fig. 1. On this table a line OS was drawn parallel to, but at an unknown distance from, the edges AD and BC. Then a ball was rolled on the table N times in succession from the edge AD toward the edge BC. As indicated in the figure, it was noted that T times the ball stopped rolling to the right of the line OS and $N - T$ times to the left of that line.

What light does this information shed on the unknown distance from AD to OS? In more technical terms, what is the *a posteriori* probability that the unknown position of the line OS lies between any two positions in which we may be interested?

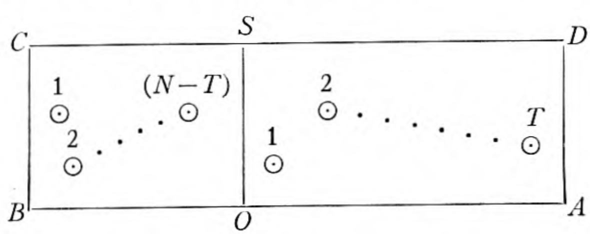


Fig. 1.

Each rolling of the ball was executed in such a manner that the probability of the ball coming to rest to the right of OS is given by the unknown ratio of the distance OA to the length BA of the table; likewise, the probability of the ball stopping to the left of OS is given by the ratio of the distance BO to the length BA.

$$\text{Set } x = OA/BA, \qquad 1 - x = BO/BA.$$

The only difference between this problem and the bag of balls problem is that now the possible values of x are not restricted to the finite set $0/M, 1/M, 2/M, \cdots (M-1)/M, M/M$; in the table problem x may have had any value whatever between the limits 0 and 1. Therefore equation (3) will answer the question asked provided we substitute definite integrals in place of the finite summations. This substitution gives us, for the desired *a posteriori* probability that x had a value between x_1 and x_2, the formula

$$P(x_1, x_2) = \frac{\int_{x_1}^{x_2} w(x)x^T(1-x)^{N-T}dx}{\int_0^1 w(x)x^T(1-x)^{N-T}dx}. \tag{4}$$

Equation (4) is useless until the form of the *a priori existence* function $w(x)$ is specified; this depends on the *way* in which the line OS was drawn. Bayes assumed that the line OS, of unknown distance from AD, was drawn through the point of rest corresponding to a preliminary roll of the ball. This amounts to postulating that all values of x, between 0 and 1, were *a priori* equally likely. In other words, with Bayes, the *a priori existence* function $w(x)$ was a constant which, therefore, did not have to be taken into consideration.[3] Thus, instead of equation (4), Bayes gave the equivalent of the following restricted formula:

$$P(x_1, x_2) = \frac{\int_{x_1}^{x_2} x^T(1-x)^{N-T}dx}{\int_0^1 x^T(1-x)^{N-T}dx}; \tag{5}$$

I say "the equivalent of" (5) because in Bayes' day definite integrals were expressed in terms of corresponding areas.

Equation (5) constitutes Proposition 9 of the essay, but is usually referred to as Bayes' theorem.

[3] The existence function $w(x)$ does not appear either explicitly or implicitly anywhere in Bayes' essay. This fact raises the question as to whether or not Bayes had any notion of the *general* problem of causes.

IV

Equation (5) is a very beautiful formula; but we must be cautious. More than one high authority has insinuated that its beauty is only skin deep. Speaking of Laplace's generalization and extension of the theorem, George Chrystal, the English mathematician and actuary, closed a severe attack on the whole theory of *a posteriori* probability [4] with the statement that "Practical people like the Actuaries, however much they may justly respect Laplace, should not air his weaknesses in their annual examinations. The indiscretions of great men should be quietly allowed to be forgotten."

Chrystal's advice as to the attitude one should assume toward "the indiscretions of great men" is excellent, but in the case under consideration, it was the plaintiff rather than the defendant who committed indiscretions; this is discussed in a paper by E. T. Whittaker [5] entitled "On Some Disputed Questions of Probability."

The discussions and disputes, which began shortly after the birth of the formula in 1763 and which have not as yet subsided, may be divided into two classes:

1. Discussions concerning problems in which it is known that the *a priori* existence function is not a constant.
2. Discussions concerning problems in which nothing whatever is known concerning the *a priori* existence function.

The discussions of Class 1 are out of order in so far as Bayes' theorem is concerned; recourse should be had to formula (4), Laplace's generalization of the Bayes' theorem, when it is known that $w(x)$ is not a constant. Failure to differentiate explicitly between equations (4) and (5) has created a great deal of confusion of thought concerning the probability of causes. The discussions of Class 2 have centered on what Boole called "the equal distribution of our knowledge, or rather of our ignorance," that is to say "the assigning to different states of things of which we know nothing, and upon the very ground that we know nothing, equal degrees of probability." Regarding the legitimacy of this procedure Bayes himself contributed a very important scholium which appeared in his essay on pages 392 and 393. The argument in this scholium, based on a corollary to Proposition 8 of the essay, may be summarized as follows:

Assuming that all values of x are *a priori* equally likely and that the N throws of a ball on the table have *not yet* been made, the probability

[4] "On Some Fundamental Principles in the Theory of Probability," *Transactions of the Actuarial Society of Edinburgh*, Vol. 11, No. 13.

[5] *Transactions of the Faculty of Actuaries in Scotland*, Vol. VIII, Session 1919–1920.

that T times the ball will rest to the right of OS and that the remaining $N - T$ times it will rest to the left of OS is (as shown in the corollary)

$$P = \int_0^1 \binom{N}{T} x^T(1-x)^{N-T}dx = \frac{1}{N+1}, \tag{6}$$

a result in which T does not appear. In other words, any assigned outcome for the throws is no more, or no less, likely than any other outcome, if *a priori* all values of x are equally likely. But, wrote Bayes in the scholium, when we say that we have no knowledge whatever *a priori* regarding the ratio x, do we not really mean that we are in the dark as to what will be the outcome when we proceed to make N throws? If so, then equation (6) justifies the assumption that *a priori* all values of x are equally likely.

To clinch his argument it must be shown that the converse of equation (6) is true. That is, it must be shown that, if any outcome of throws *not yet* made is as likely as any other, then any value of x is *a priori* as likely as any other. This converse theorem was submitted to Dr. F. H. Murray who obtained an elegant proof based on a theorem of Stieltjes.[6]

In view of Bayes' corollary and his scholium, an analysis of our bag problem with reference to the "equal distribution of our knowledge, or ignorance" is in order.

Consider again Case 1 where each drawn ball is replaced in the bag before the next drawing is made.

Assuming each of the $(M + 1)$ permissible hypotheses to be *a priori* equally likely, the probability that N drawings, *not yet* made, will result in T white and $N - T$ black balls is

$$P = \sum_{k=0}^{M} \frac{1}{M+1} \binom{N}{T} \left(\frac{k}{M}\right)^T \left(1 - \frac{k}{M}\right)^{N-T}. \tag{7}$$

Equation (7) is not, in general, independent of T,[7] so that any one assigned outcome of N drawings is not as likely as any other outcome. This result is disturbing; at first sight it seems to discredit Bayes' scholium. We must, therefore, look into the matter more closely.

Bayes' problem corresponds to drawings from a bag containing an infinite number of balls. Therefore, even if drawn balls are replaced,

[6] *Bulletin of the American Mathematical Society*, February 1930.

[7] Consider, for example, the case of $M = 2$. Equation (7) reduces to

$$P = \frac{1}{3}\left(\frac{1}{2}\right)^N \binom{N}{T},$$

a result which is not independent of T.

the chance of a particular ball being drawn more than once is zero. But when N drawings with replacements are made from a bag containing a *finite* number, M, of balls, we are by no means certain of drawing N different balls; a particular white ball may be drawn several times over and, likewise, a particular black ball may appear more than once. It is not surprising, therefore, that Case 1 of the bag problem does not confirm Bayes' corollary.

Consider now Case 2, where the drawn balls are not returned to the bag. If k of the total balls are white and the rest black, the probability that a sample of N balls from the bag will contain T white and $N - T$ black is

$$\binom{k}{T}\binom{M-k}{N-T} \Big/ \binom{M}{N}.$$

Hence, if the permissible values 0, 1, 2, 3, $\cdots$ M for k are all equally likely *a priori*, we obtain instead of (7),

$$P = \sum_{k=0}^{M}\left(\frac{1}{M+1}\right)\binom{k}{T}\binom{M-k}{N-T} \Big/ \binom{M}{N} = \frac{1}{N+1}, \tag{8}$$

a result independent of any assigned value for T and identical with the result in the corollary to Proposition 8 of the essay.

Summary

Bayes' theorem is the answer to a special case of the general problem of causes. The special case postulates that the *a priori* existence probabilities for the various admissible causes of an observed event are equal.

In the essay Bayes recommends that his theorem be adopted whenever we find ourselves confronted with total ignorance as to which one of several possible causes produced an observed event. To justify this recommendation Bayes takes the attitude that: a state of total ignorance regarding the causes of an observed event is equivalent to the same state of total ignorance as to what the result will be if the trial or experiment has not yet been made. This interpretation is a generalization of the fact that in his billiard table problem, the assumption of equal likelihood for all possible positions of the line OS, gives equal probabilities for the various possible outcomes of a set of N ball rollings not yet made.

Laplace, Poincaré and Edgeworth [8] have shown that the *a priori existence* function $w(x)$, which appears in the Laplacian generalization

[8] Laplace: "Oeuvres," Vol. 9, p. 470. Poincaré: "Calcul des Probabilités," 2d edition, p. 255. Bowley: "F. Y. Edgeworth's Contributions to Mathematical Statistics," pp. 11 and 12.

of Bayes' theorem, is of negligible importance when the numbers N and T are large. Therefore, when this condition holds, one need not hesitate to use Bayes' restricted formula for the solution of a problem of causes.

The transmission, by Price, of Bayes' posthumous essay to the Royal Society marked an epoch in the history of the literature on probability theory. As mentioned at the beginning of this paper, Karl Pearson has called the extension of Bayes' problem the "Fundamental Problem of Practical Statistics."

Extensions to the Theory and Design of Electric Wave-Filters

By OTTO J. ZOBEL

The problem of terminal wave-filter impedance characteristics is considered in this paper, in particular that of obtaining an approximately constant wave-filter impedance in the transmitting bands of a wave-filter of any class, which is of importance where the wave-filter is terminated by a constant resistance, the usual case. The solution obtained is based upon the repeated use of the methods of deriving wave-filter structures which gave the M-types, combined with composite wave-filter principles. The results are wave-filter transducers which at one end have standard "constant k" image impedances and at the other have image impedances which can theoretically be made constant in the transmitting bands to any degree of approximation desired. Practical fixed structures are shown.

Parts I and II give this derivation and composition of wave-filter structures. Two allied subjects, respectively, the designs of networks which simulate the impedances of wave-filters, and of loaded lines, are dealt with in Parts III and IV, such designs making use of the previous results.

The four Appendices contain new reactance and wave-filter frequency theorems, particular fixed transducer designs and certain equivalents; also, a chart for determining terminal losses at the junction of such a fixed wave-filter transducer and a resistance termination. This chart supplements those previously given in a chart method of calculating wave-filter transmission losses.

Introduction

ONE important problem which frequently arises in wave-filter design is that of obtaining a terminal wave-filter impedance which is approximately a constant resistance at all frequencies in the transmitting bands. This ideal impedance characteristic is desirable where a wave-filter is terminated by such a constant resistance, as is usually the case. Under these ideal conditions, for frequencies in the transmitting bands all terminal reflection losses are avoided, and there are no impedance irregularities at the terminal junction to be reflected back through the wave-filter and produce objectionable impedance irregularities at the other end.

The design of ladder type wave-filters of any class,[1] regarded from either the theoretical or the practical standpoint, involves taking into consideration two standard image impedances; and the internal or main part of a composite wave-filter structure, called the mid-part, usually has the equivalent of one or the other of these image impedances at each terminal. These two standard image impedances are the image

[1] "Theory and Design of Uniform and Composite Electric Wave-Filters," O. J. Zobel, *B. S. T. J.*, January, 1923.

impedances [2] at the two mid-points, mid-series and mid-shunt, of the "constant k" wave-filter of that class. As defined in the first paper referred to, a "constant k" wave-filter is a reactance network of ladder type, the product of whose series and shunt impedances is $k^2 = R^2$, a constant independent of frequency, where k has the significance of being the impedance of the corresponding uniform line. It is well known that these standard, or "constant k," image impedances vary greatly with frequency over all the transmitting bands and are therefore far from satisfactory as terminal wave-filter impedances. What is needed at a terminal having such an image impedance is a terminal wave-filter transducer of the same class which at one end can be joined without impedance irregularity to the standard termination and which at the other end has a desirable terminal image impedance. Actually, this amounts to terminating a composite wave-filter in a section which has at the final terminals the image impedance desired. We may set up the ideal for this purpose as follows:

The ideal terminal wave-filter transducer of any class is a dissymmetrical wave-filter network having at one end an image impedance equal at all frequencies to the standard mid-series or mid-shunt image impedance of the "constant k" wave-filter and at the other end an image impedance which has approximately the same constant resistance value ($k = R$) *at all frequencies in the transmitting bands.*

While the principal function of such a transducer is to furnish the desired terminal image impedance, its wave-filter propagation characteristics would also be useful.

The first approximate solution previously obtained was by means of M-type wave-filter terminations; [3] that is, the terminal transducer in this case was a single mid-half section of an M-type wave-filter whose parameter m is in the neighborhood of $m = .6$. Such a section has at one end one of the two standard image impedances referred to above for all frequencies. At the other end its image impedance has the same constant resistance value within about 4 per cent over 86 per cent of every transmitting band and this has proved to be quite satisfactory for many designs. However, later design requirements, such as those for certain low pass and high pass wave-filters in carrier systems, have demanded, principally from an impedance irregularity standpoint, that the resistance terminal characteristic be more nearly constant and extend still farther toward the critical frequencies than is possible with M-type terminations so as to include in this manner a larger part of the

[2] "Transmission Characteristics of Electric Wave-Filters," O. J. Zobel, *B. S. T. J.*, October, 1924.

[3] See page 17 of paper in footnote 1.

transmitting bands. A study of this general problem has recently been made, the results of which were presented in two papers both of which appeared in the same issue of this *Journal*.[4] The terminal transducers there described consist of simple non-uniform ladder type structures whose series and shunt impedances are each arbitrarily proportional to the corresponding impedances of the "constant k" wave-filter and of two-terminal reactance networks added in series or in shunt at the terminating end to complete them. A transducer of this kind practically satisfies the ideal conditions in the transmitting bands, but it does not have a standard image impedance in the attenuating bands as is desired here. Because of the latter fact, transmission loss calculations can not be made as readily as in a composite wave-filter.

This paper gives the solution of the terminal wave-filter impedance problem by the logical extension of the use of the general systematic methods of derivation which had led to the derivation of M-type sections, and the use of composite wave-filter principles. The solution is obtained in two naturally related steps which are, first, the derivation of sections having mid-point image impedances which are desirable as terminal wave-filter impedances and, second, the formation of terminal wave-filter transducers having these image impedances at terminals. A brief outline of these steps will be given here before proceeding with the details.

The first step, the derivation of suitable terminal sections, is based upon the use of two fundamental operations for deriving structures already mentioned which are applicable to any ladder type network. One of these, *the mid-series derivation* whose operation will be designated symbolically as $D_1(s)$, derives from any prototype a more general ladder type structure whose series and shunt impedances are such functions of the prototype impedances and of an arbitrary parameter, s, that its mid-series image impedance is identical with that of the prototype and thus independent of s. Its mid-shunt image impedance is, however, a function of this arbitrary parameter, where $0 < s \leqq 1$, and is thus more general than that of the prototype at the corresponding termination. The other operation, *the mid-shunt derivation* designated as $D_2(s)$, derives from a prototype another more general structure whose mid-shunt image impedance is identical with that of the prototype but whose mid-series image impedance depends upon s. If both of these prototypes, not necessarily the same, have identical transfer constants, then both derived structures having the same value of

[4] "A Method of Impedance Correction," H. W. Bode, *B. S. T. J.*, October, 1930. "Impedance Correction of Wave-Filters," E. B. Payne, *B. S. T. J.*, October, 1930.

s will also have identical transfer constants which are functions of s. At the limiting value of the parameter, $s = 1$, each derived structure becomes identical with its prototype. The reason for the use of s as the general parameter instead of m, as in previous papers, is to permit it to take on without confusion a succession of values including m, as will be seen.

Beginning with the "constant k" wave-filter of any class as the initial prototype, these two operations are performed alternately on successive structures, which results in producing two different sequences of wave-filter structures, depending upon which of the operations is first used. These wave-filters are all of the same class and contain successively more and more elements. In Sequence 1 (see Fig. 4) the first operation is $D_1(m)$, then $D_2(m')$, $D_1(m'')$, etc., the parameters being taken in succession as $s = m, m', m''$, etc. In Sequence 2 (see Fig. 5) the first operation is $D_2(m)$, then $D_1(m')$, $D_2(m'')$, etc., with the same succession of parameters as before. Since at each derivation another single parameter is introduced, each successive structure of either sequence has one more arbitrary parameter than the preceding structure and the number of arbitrary parameters in any structure is equal to the number of alternate operations performed to obtain it from the "constant k" wave-filter. Now every section has one mid-point image impedance which is a function of all of its arbitrary parameters. Hence, this whole process is effectively one for obtaining a structure with an image impedance which contains any desired number of arbitrary parameters. The first derived structures in both sequences are the pair called M-types having the parameter m. The second derived ones will be called the pair of MM'-types with parameters m and m'; the third, the pair of $MM'M''$-types with m, m' and m''; etc. Each successive pair can have a more nearly constant resistance impedance in all transmitting bands than the preceding pair because of one additional parameter in the image impedance functions. The two members of a pair have identical transfer constants and either member can be obtained from the other, as inverse networks of impedance product R^2.

While the derived structures are wave-filters having the same transmitting bands as the "constant k" wave-filter, their propagation characteristics are otherwise more general. However, no different propagation characteristics are obtained in the successively derived structures than are possible with the first derived or M-types since all these derived structures have potentially identical transfer constants, the transfer constant of any structure being dependent upon its parameters only in their product. A simple relation is given here between these parameters, the frequencies of infinite attenuation and the critical frequencies belonging to any of these derived sections; there is a slightly different relation for each of the four general groups into which all the different classes of multiple band pass wave-filters may be divided. The MM'-types, etc., are structurally more complicated than M-types and therefore have preferential value from an impedance standpoint primarily.

The second step of this solution, the formation of terminal wave-filter transducers, is related to the first step. The method of deriving sections which possess desirable terminal image impedances furnishes through the successive operations the necessary means whereby the final impedance section can be joined to the standard "constant k" wave-filter without impedance irregularity. There are two such general transducers, the series terminal transducer which connects to the standard mid-series image impedance and the shunt terminal transducer which connects to the standard mid-shunt image impedance. Obviously the *series terminal transducer* is obtained from the wave-filters of Sequence 1 and is formed by connecting in tandem mid-half sections of successive derived structures, beginning with the series M-type and ending in the one having the desired image impedance. At each junction point, always between dissimilar sections, the image impedances are identical and in every case it is possible to merge the adjacent series or shunt impedances, thereby considerably reducing the total number of elements in the entire network. This composite wave-filter has the same number of dissimilar mid-half sections as there are arbitrary parameters in the final image impedance function and the sections are functions of one or more of these same parameters, containing in succession m, m and m', m and m' and m'', etc., the final terminal section containing all parameters. The image impedance at one end of this transducer is entirely independent of all these parameters, being equal at any frequency to the mid-series image impedance of the standard "constant k" wave-filter; that at the other end depends upon them all. Fixing the final impedance characteristic determines all these arbitrary parameters and therefore all the sections making up the transducer. The propagation characteristics of these sections, while similar in form, are all different in frequency placement, being like those of M-types having successive parameters equal to the products m, mm', $mm'm''$, etc. Since m, m', m'', etc., are each less than unity, these products form a decreasing sequence. As a result, the attenuation peaks of successive sections are progressively nearer the critical frequencies and their combination builds up desirable attenuation characteristics.

The *shunt terminal transducer* is obtained in an exactly similar manner, but uses the wave-filters of Sequence 2 and begins with the shunt M-type.

Any pair of these transducers having the same number and values of the parameters have identical transfer constants; moreover, either network might be obtained from the other, as inverse networks of impedance product R^2.

Theoretically, with dissipation neglected, the solution of the terminal wave-filter impedance problem, as outlined above, can be carried to any degree of approximation desired toward a constant resistance terminal image impedance in all transmitting bands. Practically, however, it is here found unnecessary to go beyond the MM'-types which follow in sequence directly after the well-known M-types and are thus comparatively simple extensions. They meet the desired impedance ideal well and are in this respect a considerable improvement over the M-types just as the latter are an improvement over the "constant k" wave-filter, as we might expect. By a proper choice of the parameters m and m' it will be shown later that the MM'-types can be made to have image impedances which are equal to the same constant resistance within 2 per cent over the greater part of all transmitting bands. In low pass and band pass wave-filters this nearly constant resistance extends over a frequency range which is approximately equal to 96 per cent of the theoretical band width. Similar characteristics apply to wave-filters of other classes. Such a range includes all of a transmitting band except a small region next to each critical frequency where, however, the wave-filter attenuation makes it practically useless for transmitting purposes. Each terminal transducer would then be a composite wave-filter made up of a mid-half section of the associated M-type of parameter m and a mid-half section of such an MM'-type of parameters m and m'. While, as already stated, the M-types and MM'-types have potentially the same propagation characteristics, the particular values of the parameters m and m' chosen from the impedance standpoint give attenuation peaks which in these M-types are farther away from the critical frequencies, and in these MM'-types nearer, than in an M-type of parameter $m = .6$, which is generally desirable. Two such fixed designs [5] are given here for connection to the "constant k" wave-filter of any class at mid-series or at mid-shunt, respectively. The particular forms these take

[5] The reader should keep in mind that such a terminal wave-filter network is itself a true composite wave-filter of the same class as the standard or "constant k" wave-filter. Its image impedance at one end is the same as a mid-point image impedance of the standard, while that at the other end is the mid-point image impedance of the MM'-type which is desired at the terminal.

in the four most important specific classes, namely, low pass, high pass, low-and-high pass and band pass, are also shown.

Finally, two by-products obtained from a further use of these fixed network designs will be added. One is the ready design of networks to simulate the mid-point image impedances of "constant k" wave-filters. The other leads to the design of networks which simulate the impedances of a loaded line, approximately a low pass wave-filter, over the greater part of its transmitting band.

It need hardly be mentioned that these terminal transducers may be used to terminate a lattice or other type of wave-filter which has a standard image impedance or, vice versa, that of a derived wave-filter such as the MM'-type. In this manner the terminal image impedance can be altered efficiently from one characteristic to another. The lattice type (z_1, z_2) is itself a symmetrical structure.

The procedure for the design of a wave-filter network to meet specific requirements may even begin with the choice of terminal wave-filter impedance characteristics, which are physical and not in general the same at both ends. The terminal, or reflection, losses due to resistance or other known terminating impedances would thus be definitely known. With these taken into account the internal part would be designed using any type or types so as to fit in between the chosen image impedances without impedance irregularity, as in a composite structure, and give the remainder of the desired transmission characteristic.

Part 1. Derivation of Wave-Filters Which Possess Desirable Image Impedances

1.1 General Ladder Type Structure

Of the three simple general types of recurrent or iterative structures, the ladder, lattice and bridged-T types, only the ladder type which has alternate series and shunt impedances, z_1 and z_2, respectively, has two different image impedances per periodic interval and these are W_1 and W_2 at the two mid-points, mid-series and mid-shunt. The ladder type can therefore be separated on the image basis into either of two kinds of symmetrical sections with two pairs of terminals, mid-series or mid-shunt sections, or into one kind of dissymmetrical section, a mid-half section. The existence of two different image impedances for a section, the general property of all mid-half sections, is a necessary condition for the proper combination of mid-half sections of different related structures to give the desirable terminal impedance results obtained in this paper. Definitions of these three kinds of sections which have been considered in previous papers will be reviewed here.

A mid-series section is that part between the mid-point of one series impedance z_1 and the mid-point of the next series impedance. It has the three impedance branches $\frac{1}{2}z_1$, z_2, and $\frac{1}{2}z_1$ and has the structure of a T-network. Its image impedance at each end is the mid-series image impedance W_1.

A mid-shunt section is that part between the mid-point of one shunt admittance $1/z_2$ and the mid-point of the next shunt admittance. It

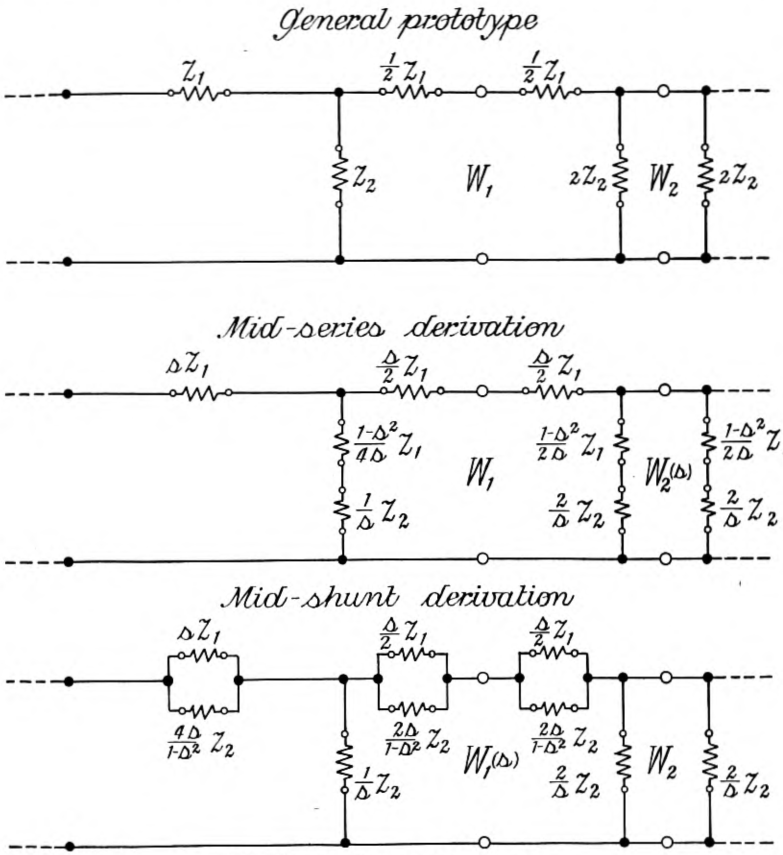


Fig. 1—Fundamental derivations.
$0 < s \leqq 1$.

has the three impedance branches $2z_2$, z_1, and $2z_2$ and has the structure of a π-network. Its image impedance at each end is the mid-shunt image impedance W_2. Both of the above symmetrical sections have the same transfer constants, T, as we should expect since both sections represent one full interval of the ladder type structure.

A mid-half section is that dissymmetrical part between the mid-point of one series impedance and the mid-point of the next shunt admittance, or vice versa. The image impedances at the two ends are, respectively, W_1 and W_2, or vice versa. Its transfer constant is one-half that of a full section, mid-series or mid-shunt. Obviously, two mid-half sections when connected with like image impedances, W_2 or W_1, adjacent, will form a mid-series or mid-shunt section, respectively.

Well-known formulas for the transfer constant, T, of a full section and for the mid-series and mid-shunt image impedances, W_1 and W_2, are

$$\cosh T = \cosh (A + iB) = 1 + \frac{z_1}{2z_2} = 1 + 2(U + iV),$$

$$W_1 = \sqrt{z_1 z_2 + \tfrac{1}{4}z_1^2} = \sqrt{z_1 z_2}\sqrt{1 + U + iV},$$

and

$$W_2 = \frac{z_1 z_2}{\sqrt{z_1 z_2 + \tfrac{1}{4}z_1^2}} = \frac{\sqrt{z_1 z_2}}{\sqrt{1 + U + iV}} = \frac{z_1 z_2}{W_1}, \tag{1}$$

where

$$U + iV = \frac{z_1}{4z_2} \cdot$$

Such a general structure is illustrated in the upper part of Fig. 1.

1.2 Fundamental Derivations

1.21 Mid-Series Derivation by Operation $D_1(s)$

From any ladder type network z_1, z_2 it is possible to derive a more general one $z_1'(s)$, $z_2'(s)$ which has the same mid-series image impedance W_1 as the prototype, but a transfer constant $T(s)$ and a mid-shunt image impedance $W_2(s)$ which are functions of an arbitrary parameter s. This operation, denoted as $D_1(s)$, is specified by the mathematical and physical relations between the series and shunt impedances of the derived network and those of the prototype, namely,[6]

$$z_1'(s) = sz_1,$$

and

$$z_2'(s) = \frac{1 - s^2}{4s} z_1 + \frac{1}{s} z_2, \tag{2}$$

where $0 < s \leqq 1$ for a physical structure. At the limit $s = 1$, it reduces to the prototype. (The superscript "prime" refers to the case of mid-series equivalence.)

[6] See footnote 3. Also U. S. Patent No. 1,538,964 to O. J. Zobel, dated May 26, 1925.

These relations give for the derived structure in terms of its prototype and parameter s

$$\cosh T(s) = 1 + 2(U(s) + iV(s)),$$

$$W_1 = W_1,$$

and

$$W_2(s) = W_2[1 + (1 - s^2)(U + iV)], \qquad (3)$$

where

$$U(s) + iV(s) = \frac{s^2(U + iV)}{1 + (1 - s^2)(U + iV)}.$$

By the above operation a new image impedance $W_2(s)$ has been obtained which is more general than the mid-shunt image impedance of the prototype.

1.22 Mid-Shunt Derivation by Operation $D_2(s)$

From any ladder type network z_1, z_2 it is possible to derive a more general one $z_1''(s)$, $z_2''(s)$ which has the same mid-shunt image impedance W_2 as the prototype, but a transfer constant $T(s)$ and a mid-series image impedance $W_1(s)$ which are functions of an arbitrary parameter s. This operation, denoted as $D_2(s)$, is specified by these mathematical and physical relations between the derived network and its prototype

$$z_1''(s) = \frac{1}{\dfrac{1}{sz_1} + \dfrac{1}{\dfrac{4s}{1 - s^2} z_2}},$$

and $\qquad (4)$

$$z_2''(s) = \frac{1}{s} z_2,$$

where $0 < s \leqq 1$ for a physical structure. At the limit $s = 1$, it reduces to the prototype. (The superscript "second" refers to the case of mid-shunt equivalence.)

From these relations it follows that the derived structure has

$$\cosh T(s) = 1 + 2(U(s) + iV(s)),$$

$$W_1(s) = \frac{W_1}{1 + (1 - s^2)(U + iV)},$$

and $\qquad (5)$

$$W_2 = W_2,$$

where

$$U(s) + iV(s) = \frac{s^2(U + iV)}{1 + (1 - s^2)(U + iV)}.$$

This operation gives a new image impedance $W_1(s)$ which is more general than the corresponding one of the prototype.

The derived structures represented by formulas (2) and (4) as well as their common prototype are given in Fig. 1. A comparison of formulas (1) to (5) shows that for the same value of the parameter s both derived networks have the same transfer constant $T(s)$ and that

$$z_1'(s)z_2''(s) = z_1''(s)z_2'(s) = W_1W_2 = W_1(s)W_2(s) = z_1z_2.$$

Thus the series and shunt impedances of one derived structure are inverse networks of impedance product z_1z_2 of the shunt and series impedances, respectively, of the other one derived from the same prototype, z_1, z_2. Similarly, the pair of image impedances W_1 and W_2 and the pair $W_1(s)$ and $W_2(s)$ are inverse impedances of this same product. In fact, either infinite structure might have been obtained from the other as such an inverse network; the transfer constants of the two would then necessarily be identical for the ratio of series to shunt impedance would be the same in both.

1.3 "Constant k" Wave-Filter, The Initial Prototype

The "constant k" wave-filter of any class, that is, having any preassigned transmitting and attenuating bands, is a reactance network of ladder type whose product of series and shunt impedances, and therefore iterative impedance k of the corresponding uniform line, is a constant independent of frequency. Putting k equal to the resistance R of the line or impedance with which the wave-filter is normally to be associated, we have

$$z_{1k}z_{2k} = k^2 = R^2 = \text{a constant}.$$

Here and in what follows the additional subscript k implies a relation to the "constant k" wave-filter.

When there is dissipation in the reactance elements, the above relation is strictly satisfied by requiring that the coil dissipation constant, d, and the condenser dissipation constant, d', be equal for each pair of inverse network elements. For example, when $d = d'$

$$\frac{(d + i)2\pi f L_{1k}}{(d' + i)2\pi f C_{2k}} = \frac{L_{1k}}{C_{2k}} = R^2.$$

There are several reasons for choosing the "constant k" wave-filter as the initial prototype.

1. Its structure and method of design for any class is definitely known.[7]

[7] See footnote 1. Also U. S. Patent No. 1,509,184 to O. J. Zobel, dated September 23, 1924.

2. It has both standard image impedances, each of which passes through the same cycle of values in all transmitting bands.
3. Each M-type or wave-filter of higher order derived from it can have an improved impedance characteristic which is the same in all transmitting bands.
4. The assumption that its impedances z_{1k} and z_{2k} are general in the analysis makes the results independent of any particular class of wave-filter and hence applicable to all classes.
5. This method of analysis sorts out certain valuable properties which are common to all classes by treating known groups of meshes, z_{1k} and z_{2k}, as units, thereby eliminating the necessity of considering each individual mesh which may be present in the interior of z_{1k} and z_{2k} of any particular class.

It will be appreciated by the reader that the difficulties of the problem for one of the higher classes of wave-filters are thus greatly reduced over what they would be if each mesh had to be taken into account, as might be required by other methods.

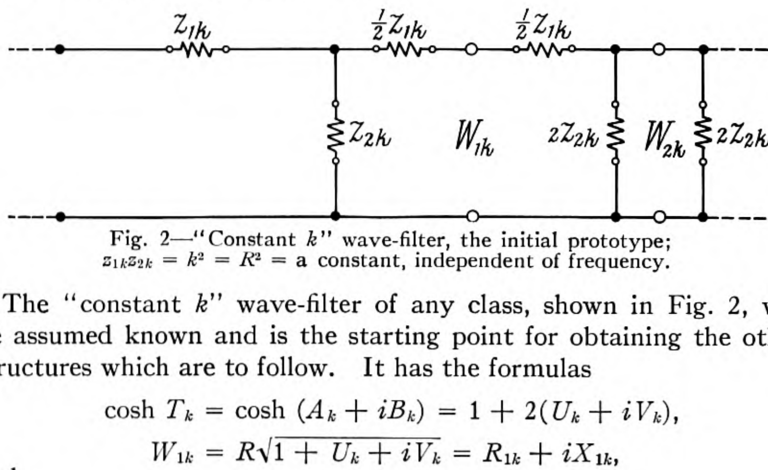


Fig. 2—"Constant k" wave-filter, the initial prototype; $z_{1k}z_{2k} = k^2 = R^2$ = a constant, independent of frequency.

The "constant k" wave-filter of any class, shown in Fig. 2, will be assumed known and is the starting point for obtaining the other structures which are to follow. It has the formulas

$$\cosh T_k = \cosh (A_k + iB_k) = 1 + 2(U_k + iV_k),$$
$$W_{1k} = R\sqrt{1 + U_k + iV_k} = R_{1k} + iX_{1k},$$

and

$$W_{2k} = \frac{R}{\sqrt{1 + U_k + iV_k}} = \frac{R^2}{W_{1k}} = R_{2k} + iX_{2k};$$

where

$$T_k = \text{transfer constant of a full section,} \tag{6}$$
$$\tfrac{1}{2}T_k = \text{transfer constant of a mid-half section,}$$
$$W_{1k} = \text{image impedance at a series mid-point,}$$
$$W_{2k} = \text{image impedance at a shunt mid-point,}$$
$$U_k + iV_k = \frac{z_{1k}}{4z_{2k}} = \left(\frac{z_{1k}}{2R}\right)^2,$$

and

$$R^2 = z_{1k}z_{2k} = k^2 = \text{a constant.}$$

It will be noted from these formulas that the transfer constant and both image impedances of any "constant k" wave-filter are functions of frequency only through the variables $U_k + iV_k$, or the equivalent $(z_{1k}/2R)^2$ which is a function of z_{1k}. (It would also have been possible to use z_{2k} instead of z_{1k}.) When no dissipation in the elements is assumed, $z_{1k} = r_{1k} + ix_{1k}$ becomes $z_{1k} = ix_{1k}$, a pure reactance, since then $r_{1k} = 0$; also $V_k = 0$. Under these ideal conditions we know that x_{1k} always has a positive slope with frequency,[8] and when the x_{1k} of a multiple band wave-filter is plotted against frequency it is made up of *negative branches* from $x_{1k} = -\infty$ to 0 and *positive branches* from $x_{1k} = 0$ to $+\infty$ which lie alternately in succession along the frequency scale. These branches are defined to correspond with the sign of x_{1k}. The value of U_k is always negative and ranges continuously with frequency between the values $U_k = 0$ and $-\infty$, once for each branch of x_{1k}. We know also that in a negative branch there is a transmitting band at frequencies corresponding to values from $x_{1k} = -2R$ to 0, and thus from $U_k = -1$ to 0. In a positive branch there is a transmitting band from $x_{1k} = 0$ to $+2R$, thus from $U_k = 0$ to -1. A low pass band is associated with a positive branch which begins at zero frequency while a high pass band is associated with a negative branch ending at infinite frequency. An internal transmitting band, on the other hand, has this association with a pair of branches, a negative followed on the frequency scale by a positive branch, and in reality consists of two bands which are confluent at $x_{1k} = 0$, i.e., $U_k = 0$, where the two branches join. Such a confluent band is formed by the junction of two bands which occur separately in a wave-filter of higher class than this "constant k" wave-filter but with the same configuration of elements.

Since all negative branches are similar, as well as all positive branches, an approximate representation of the frequency characteristics of any "constant k" wave-filter can be constructed from the characteristics which belong to each of these two kinds of branches. It is necessary to consider both a negative branch and a positive branch since the characteristics of one branch differ in their variations with frequency from those of the other. Differences would naturally be expected from the fact that in formulas (6) which hold for both branches the variable U_k varies with increasing frequency from $U_k = -\infty$ to 0 in a negative branch and from $U_k = 0$ to $-\infty$ in a

[8] See page 5 of paper in footnote 1.

positive branch. When $V_k = 0$, as when no dissipation is assumed, the formulas become functions of U_k only but contain a certain indeterminateness regarding the signs attributable to the phase constants and image impedance reactances of the two branches. This difficulty vanishes when dissipation is present to give V_k a value different from zero, as in a physical wave-filter.

With dissipation such as to preserve the "constant k" relation it is readily shown that V_k is negative in a negative branch and positive in a positive one; that is, *V_k has the sign of x_{1k}.* This follows directly from the formula

$$U_k + iV_k = \left(\frac{z_{1k}}{2R}\right)^2 = \frac{(r_{1k}^2 - x_{1k}^2)}{4R^2} + i\frac{r_{1k}x_{1k}}{2R^2},$$

since r_{1k} must be a positive resistance in a passive network. On the basis of this result it follows from formulas (6) that[9] *in a negative branch*

$$x_{1k},\ V_k,\ B_k \text{ and } X_{1k} \text{ are negative;}$$
$$x_{2k} \text{ and } X_{2k} \text{ are positive.}$$

In a positive branch these signs are reversed.

The characteristics of two such representative branches are shown in Fig. 3, joined as they would be to form an internal transmitting band. The scale of abscissas is U_k rather than frequency in order to be general, and U_k varies in going from left to right from $-\infty$ to 0 for the negative branch and from 0 to $-\infty$ for the positive branch. In this way a movement along the abscissa-axis from left to right always corresponds to an increase in frequency. A translation from the U_k to the frequency-scale can be obtained in any particular case through the known relationship between U_k and frequency. Such a translation would be equivalent to a variable expansion or contraction of the above characteristics parallel to the abscissa-axis. The effects of dissipation on the different characteristics are indicated by broken lines and show a rounding-off of abrupt changes. Here, for convenience, it was assumed that $V_k = .01\,U_k$ in a negative branch and $V_k = -\,.01\,U_k$ in a positive branch. If each pair of characteristics is considered as separated by an imaginary line perpendicular to the U_k-axis at $U_k = 0$, then a comparison will yield the statement that corresponding pairs of A_k, R_{1k} and R_{2k} are images of each other with respect to such lines, while pairs of B_k, X_{1k} and X_{2k} are images but also opposite in sign.

[9] See also page 577 of paper in footnote 2.

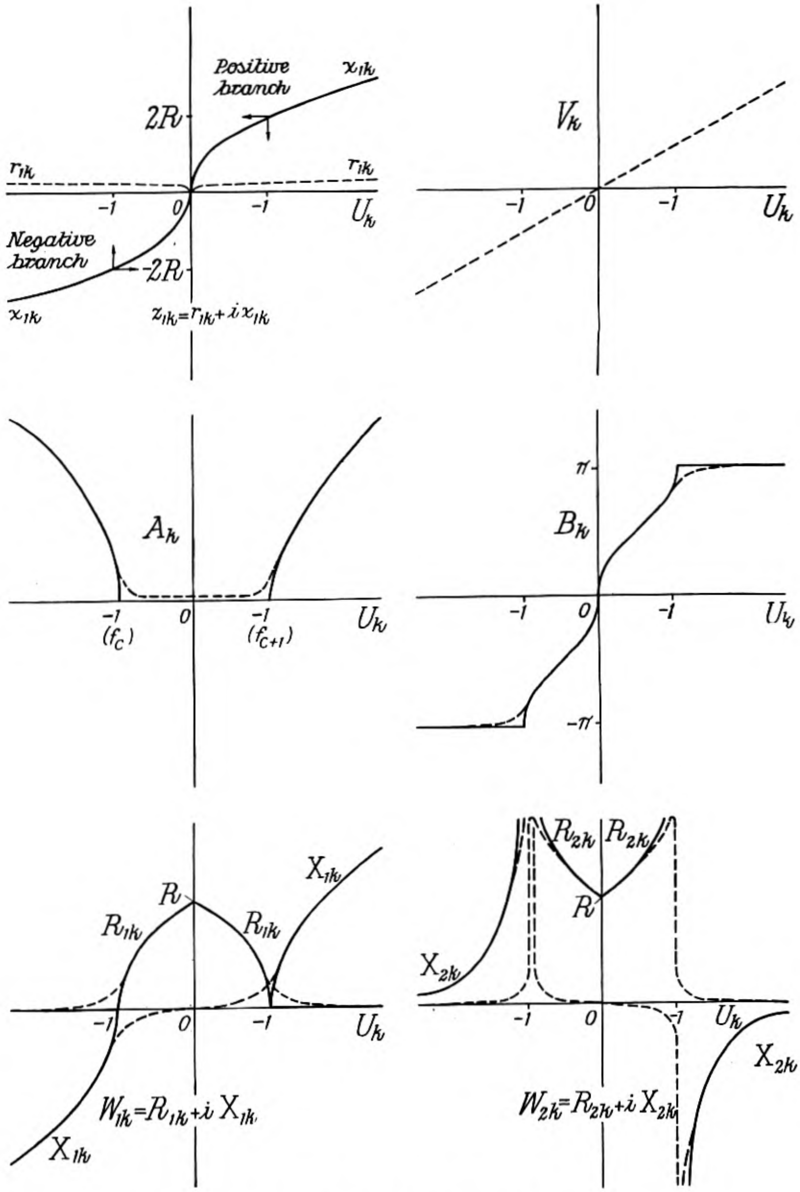


Fig. 3—Characteristics of "constant k" wave-filters. (Broken lines indicate the effects of dissipation.)

1.4 Sequence 1

As already stated in the Introduction to this paper, the successive wave-filter structures of any class which comprise Sequence 1 are derived from the known "constant k" wave-filter taken as the initial prototype by performing in succession the operations $D_1(m)$, then $D_2(m')$, $D_1(m'')$, etc. They may be considered as wave-filters of higher and higher order since they contain a greater and greater number of arbitrary parameters. The parameters of the alternate operations $D_1(s)$ and $D_2(s)$ are in the order of $s = m, m', m''$, etc.

The small letter m with superscripts is used as the notation for all the parameters in order to denote their association with "mid" of mid-point impedances, since mid-points are under consideration here in ladder type networks. Where the initial prototype is the "constant k" wave-filter, as it is here, I have used a terminology for the derived structures whose basis is the capital letter M with superscripts to correspond with those of the associated small letter parameters. Thus, I have shortened the expression "mid-series derived, parameter m ladder type" to "series M-type"; similarly for the other structures.

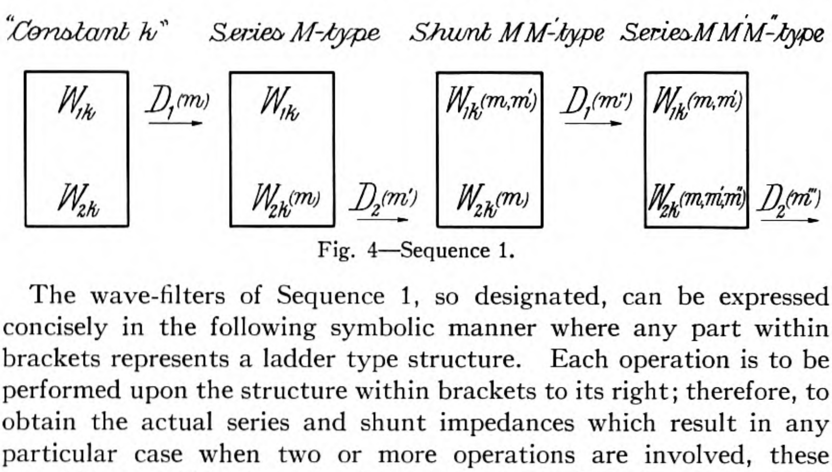


Fig. 4—Sequence 1.

The wave-filters of Sequence 1, so designated, can be expressed concisely in the following symbolic manner where any part within brackets represents a ladder type structure. Each operation is to be performed upon the structure within brackets to its right; therefore, to obtain the actual series and shunt impedances which result in any particular case when two or more operations are involved, these operations would begin at the right with $D_1(m)$ on $[k]$, the "constant k" wave-filter.

$$\begin{aligned} \text{"Constant } k\text{"} &= [k], \\ \text{Series } M\text{-type} &= D_1(m)[k], \\ \text{Shunt } MM'\text{-type} &= D_2(m')[D_1(m)[k]], \\ \text{Series } MM'M''\text{-type} &= D_1(m'')[D_2(m')[D_1(m)[k]]], \text{ etc.} \end{aligned} \tag{7}$$

A diagram which illustrates this process and gives as well the notation of the resulting image impedances in the successive structures of Sequence 1 is shown in Fig. 4. Each rectangle represents a wave-filter of ladder type having the two mid-point image impedances as indicated. The operation symbol between each succeeding pair of rectangles shows what operation has been performed and the arrow points towards the derived structure of higher order, being placed in line with the image impedances which are identical for the pair. Thus it is seen that each derived structure has one identical and one more general image impedance than the preceding structure. In the sequence the new image impedances appear alternately at mid-series and mid-shunt points, beginning with the latter here.

The series and shunt impedances of the different structures which become more and more complicated with increase in parameters are derived by performing the above operations but their detailed consideration will be deferred to a later point.

The transfer constants of the various members of this sequence are found by carrying out the proper operations based upon formulas (3), (5) and (6) and can be expressed by one formula, namely

$$\cosh T_k(g) = 1 + \frac{2g^2(U_k + iV_k)}{1 + (1 - g^2)(U_k + iV_k)}, \tag{8}$$

where $g = 1$, m, mm', $mm'm''$, etc., in a decreasing sequence.[10] The value of g for the structure of any order is equal to the product of all of its parameters, the first value above, $g = 1$, being that of the "constant k" wave-filter. This is, for example, because by (3)

$$U_k(m, m', m'') + iV_k(m, m', m'') = \frac{m^2m'^2m''^2(U_k + iV_k)}{1 + (1 - m^2m'^2m''^2)(U_k + iV_k)}. \tag{9}$$

The image impedances in Sequence 1 which are derived in a corresponding manner have these formulas.

$$\begin{aligned} W_{1k} &= W_{1k}, \\ W_{2k}(m) &= W_{2k}[1 + a(U_k + iV_k)], \\ W_{1k}(m, m') &= \frac{W_{1k}[1 + a(U_k + iV_k)]}{[1 + a'(U_k + iV_k)]}, \\ W_{2k}(m, m', m'') &= \frac{W_{2k}[1 + a(U_k + iV_k)][1 + a''(U_k + iV_k)]}{[1 + a'(U_k + iV_k)]}, \text{ etc.,} \end{aligned} \tag{10}$$

[10] Computations for the transfer constant can be made accurately from formulas for $\cosh^{-1}(x + iy)$ given in Appendix III of the paper "Distortion Correction in Electrical Circuits with Constant Resistance Recurrent Networks," O. J. Zobel, *B. S. T. J.*, July, 1928.

where

$$a = 1 - m^2,$$
$$a' = 1 - m^2 m'^2,$$
$$a'' = 1 - m^2 m'^2 m''^2, \text{ etc.,}$$

in an increasing sequence approaching unity. W_{1k} and W_{2k} are the "constant k" image impedances of formulas (6). The continuation of this series of image impedances is quite obvious, a new factor appearing alternately in the numerator and in the denominator.

Each factor in the numerator gives the image impedance a resonant point in an attenuating band where the image impedance is a reactance and $U_k < -1$; that is, at $U_k = -1/a$, or $-1/a''$, etc., neglecting dissipation with $V_k = 0$. A factor in the denominator gives an anti-resonant point; at $U_k = -1/a'$, etc. Since a' lies between a and a'', etc., these resonant and anti-resonant points alternate as in a general reactance network. Only the resonant or anti-resonant point due to the new factor added coincides with the point of infinite attenuation in the corresponding new structure, as may be seen upon comparing formulas (8) and (10), neglecting dissipation. These properties outside a transmitting band may or may not be desirable in certain kinds of circuits. They are of importance when considering terminal losses in an attenuating band, as in Section 2.6.

1.5 Sequence 2

Here the derived structures are obtained by performing in succession the operations $D_2(m)$, then $D_1(m')$, $D_2(m'')$, etc., where the initial

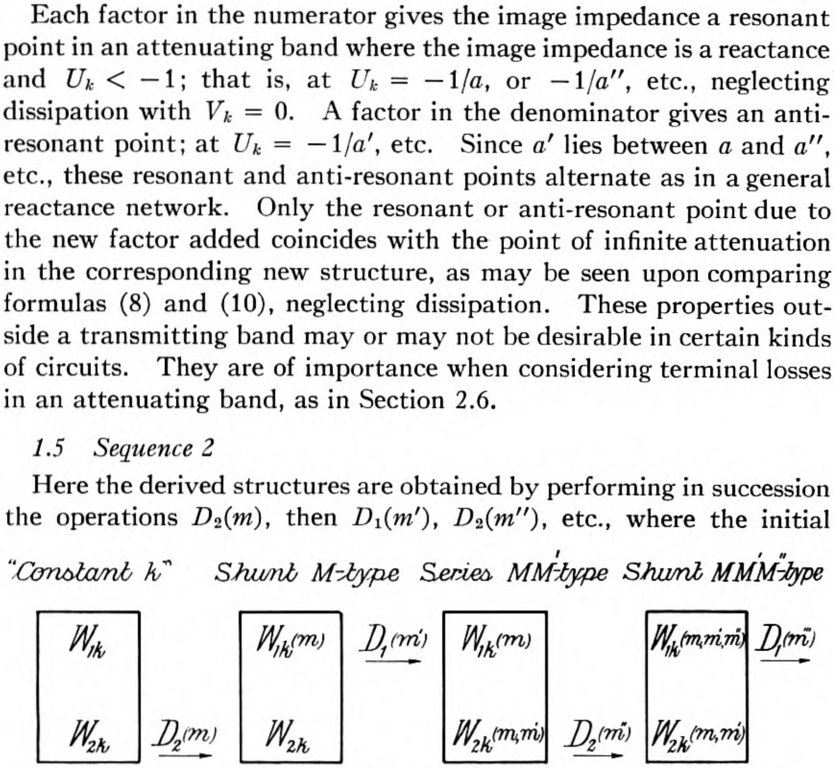


Fig. 5—Sequence 2.

prototype is the "constant k" wave-filter. Using the same notation and terminology as before, the wave-filters of Sequence 2 when expressed symbolically are

$$\begin{aligned} \text{"Constant } k\text{"} &= [k], \\ \text{Shunt } M\text{-type} &= D_2(m)[k], \\ \text{Series } MM'\text{-type} &= D_1(m')[D_2(m)[k]], \\ \text{Shunt } MM'M''\text{-type} &= D_2(m'')[D_1(m')[D_2(m)[k]]], \text{ etc.} \end{aligned} \tag{11}$$

A corresponding diagram which illustrates this process is that of Fig. 5.

The transfer constants of these wave-filters are also given by formula (8) which includes (9).

The image impedances in Sequence 2 are

$$\begin{aligned} W_{2k} &= W_{2k}, \\ W_{1k}(m) &= \frac{W_{1k}}{[1 + a(U_k + iV_k)]}, \\ W_{2k}(m, m') &= \frac{W_{2k}[1 + a'(U_k + iV_k)]}{[1 + a(U_k + iV_k)]}, \\ W_{1k}(m, m', m'') &= \frac{W_{1k}[1 + a'(U_k + iV_k)]}{[1 + a(U_k + iV_k)][1 + a''(U_k + iV_k)]}, \text{etc.,} \end{aligned} \tag{12}$$

where a, a', a'', etc., have the same values as in (10).

1.6 Relations Between Sequence 1 and Sequence 2

Carrying through operations for the determination of the structures of the series and shunt impedances in these wave-filters, the following results are found:

a. Each pair of structures of the same order in the two sequences is a pair of inverse networks of impedance product R^2.

That is, if the series M-type has the series and shunt impedances $z_{1k}'(m)$ and $z_{2k}'(m)$, and the shunt M-type $z_{1k}''(m)$ and $z_{2k}''(m)$, the inverse network relations are

$$z_{1k}'(m)z_{2k}''(m) = z_{1k}''(m)z_{2k}'(m) = R^2.$$

For the MM'-types, using similar notation,

$$z_{1k}'(m, m')z_{2k}''(m, m') = z_{1k}''(m, m')z_{2k}'(m, m') = R^2,$$

and so on for the higher order pairs. Consequently, one structure of each pair might be obtained from the other as such an inverse network.[11]

b. The transfer constants of both structures of a pair are the same.

This result would come from the inverse network relations which give both structures the same ratio of series to shunt impedances, a ratio which determines the transfer constant. It has already been found in formula (8) where the value of g is the same for both structures of any order.

[11] The structures indicated or to be shown in detail in Sequence 1 and Sequence 2 can be generalized as ladder type derivations from any initial prototype z_1, z_2. This is done by a simple replacement of z_{1k} and z_{2k} by z_1 and z_2, respectively; of R^2 by the product z_1z_2; and by the omission of the subscripts, k, throughout.

c. The series and shunt image impedances of a pair are inverse networks of impedance product R^2.

Such results would also follow from (*a*) above together with the consideration of mid-point terminations. They are verified by comparison of formulas (10) and (12) which give

$$W_{1k}W_{2k} = W_{1k}(m)W_{2k}(m) = W_{1k}(m, m')W_{2k}(m, m') \\ = W_{1k}(m, m', m'')W_{2k}(m, m', m'') = \cdots = R^2.$$

d. Both image impedances of either MM′-type, or of either one of a higher order pair, may be adjusted dependently without changing its transfer constant; the ratio of the two image impedances is fixed when the transfer constant is fixed.

This can be seen from the fact that the transfer constant depends upon the parameters only in their product, g, and from the formulas for two consecutive impedances in (10) or (12).

1.7 M-Type Wave-Filters

These are the wave-filters of the first order in each sequence and contain one arbitrary parameter, m. Although they are quite well-known, it is necessary to include them here for the sake of continuity and because of the fact that they are to be used later.

The series M-type has the formulas

$$\begin{aligned} z_{1k}'(m) &= mz_{1k}, \\ z_{2k}'(m) &= \frac{1-m^2}{4m}z_{1k} + \frac{1}{m}z_{2k}, \\ \cosh T_k(m) &= 1 + \frac{2m^2(U_k + iV_k)}{1 + (1-m^2)(U_k + iV_k)}, \\ W_{1k} &= R\sqrt{1 + U_k + iV_k}, \end{aligned} \qquad (13)$$

and

$$W_{2k}(m) = \frac{R[1 + (1-m^2)(U_k + iV_k)]}{\sqrt{1 + U_k + iV_k}}.$$

In the shunt M-type

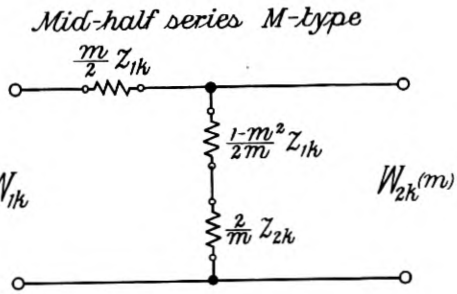
$$\begin{aligned} z_{1k}''(m) &= \frac{1}{\dfrac{1}{mz_{1k}} + \dfrac{1}{\dfrac{4m}{1-m^2}z_{2k}}}, \\ z_{2k}''(m) &= \frac{1}{m}z_{2k}, \\ \cosh T_k(m) &= \text{same as in (13)}, \\ W_{1k}(m) &= \frac{R\sqrt{1 + U_k + iV_k}}{[1 + (1-m^2)(U_k + iV_k)]}, \end{aligned} \qquad (14)$$

and

$$W_{2k} = \frac{R}{\sqrt{1 + U_k + iV_k}}.$$

In the above $0 < m \leqq 1$. At the limit $m = 1$, the two structures reduce to the "constant k" wave-filter; also $W_{1k}(m = 1) = W_{1k}$ and $W_{2k}(m = 1) = W_{2k}$.

A mid-half section of each of these wave-filters is shown in Fig. 6. It is to be remembered that the transfer constant of a mid-half section is one-half that of the full section given in the formulas.



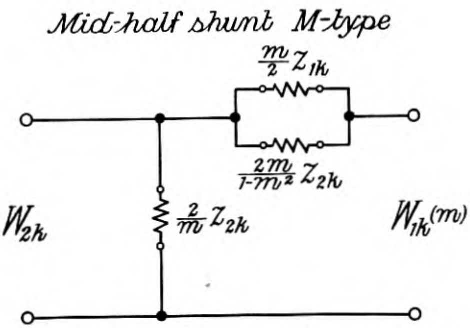


Fig. 6—Mid-half sections of M-type wave-filters.

To illustrate the propagation and impedance characteristics of M-types, as in Fig. 7, the parameter was taken to have the value $m = .6$. The attenuation constant has one maximum just beyond each critical frequency, where $U_k = -1/(1 - m^2) = -1.5625$, and in this particular case the image impedances shown have the fairly constant resistance values over a large part of each transmitting band to which reference has been made. With other values of m there may or may not be in the range from $U_k = 0$ to -1 one maximum for $W_{1k}(m)$ and one minimum for $W_{2k}(m)$. The image impedances at the other mid-points are independent of m and are identical with those of the "constant k" wave-filter already shown in Fig. 3.

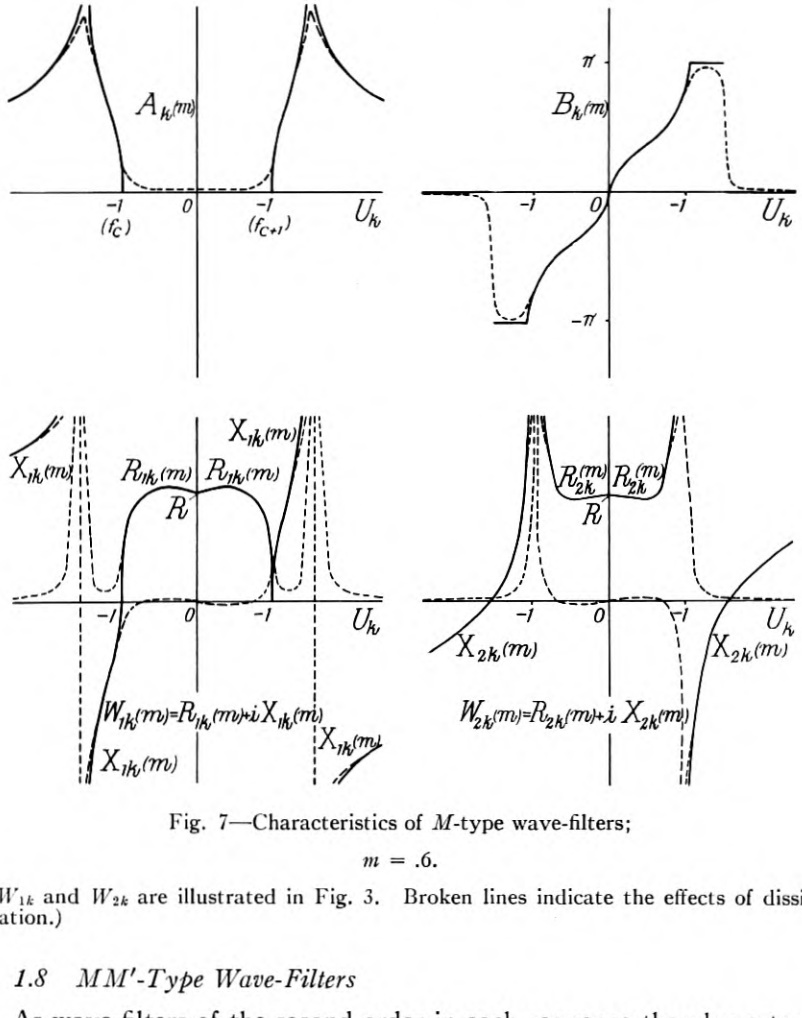


Fig. 7—Characteristics of M-type wave-filters;

$m = .6$.

(W_{1k} and W_{2k} are illustrated in Fig. 3. Broken lines indicate the effects of dissipation.)

1.8 MM'-Type Wave-Filters

As wave-filters of the second order in each sequence they have two parameters, m and m'. Their series and shunt impedances are derived by means of the single operations with parameter m' performed in the regular manner upon the M-type structures as prototypes which have the formulas (13) and (14).

Formulas for the series MM'-type are

$$
\begin{aligned}
z_{1k}'(m, m') &= \frac{1}{\dfrac{1}{mm'z_{1k}} + \dfrac{1}{\dfrac{4mm'}{1-m^2} z_{2k}}}, \\
z_{2k}'(m, m') &= \frac{1}{\dfrac{1}{\dfrac{m(1-m'^2)}{4m'} z_{1k}} + \dfrac{1}{\dfrac{m(1-m'^2)}{m'(1-m^2)} z_{2k}}} + \frac{1}{mm'} z_{2k}, \qquad (15) \\
\cosh T_k(m, m') &= 1 + \frac{2m^2m'^2(U_k + iV_k)}{1 + (1 - m^2m'^2)(U_k + iV_k)}, \\
W_{1k}(m) &= \frac{R\sqrt{1 + U_k + iV_k}}{[1 + (1 - m^2)(U_k + iV_k)]},
\end{aligned}
$$

and

$$
W_{2k}(m, m') = \frac{R[1 + (1 - m^2m'^2)(U_k + iV_k)]}{[1 + (1 - m^2)(U_k + iV_k)]\sqrt{1 + U_k + iV_k}},
$$

where $0 < m \leqq 1$, and $0 < m' \leqq 1$.

As a limiting value, $W_{2k}(m, m' = 1) = W_{2k}$.

For the shunt MM'-type

$$
\begin{aligned}
z_{1k}''(m, m') &= \frac{1}{\dfrac{1}{mm'z_{1k}} + \dfrac{1}{\dfrac{m'(1-m^2)}{m(1-m'^2)} z_{1k} + \dfrac{4m'}{m(1-m'^2)} z_{2k}}}, \qquad (16) \\
z_{2k}''(m, m') &= \frac{1-m^2}{4mm'} z_{1k} + \frac{1}{mm'} z_{2k},
\end{aligned}
$$

$\cosh T_k(m, m')$ = same formula as in (15),

$$
W_{1k}(m, m') = \frac{R[1 + (1 - m^2)(U_k + iV_k)]\sqrt{1 + U_k + iV_k}}{[1 + (1 - m^2m'^2)(U_k + iV_k)]},
$$

and

$$
W_{2k}(m) = \frac{R[1 + (1 - m^2)(U_k + iV_k)]}{\sqrt{1 + U_k + iV_k}},
$$

where as before $0 < m \leqq 1$, and $0 < m' \leqq 1$. A limiting value here is $W_{1k}(m, m' = 1) = W_{1k}$.

The MM'-type wave-filters have structural designs which can be inferred from their respective mid-half sections of Fig. 8; they may have characteristics such as illustrated in Fig. 9 where the parameters are $m = .7230$ and $m' = .4134$; the reason for this particular set of values will be explained later. The transfer constant is the same as that of an M-type of parameter equal to the product $mm' = .2989$. With other values of m and m' the image impedances $W_{1k}(m, m')$ and $W_{2k}(m, m')$, which in the transmitting bands are pure resistances if dissipation is neglected, can be given a variety of characteristics as is apparent from their formulas. In fact their physical possibilities can

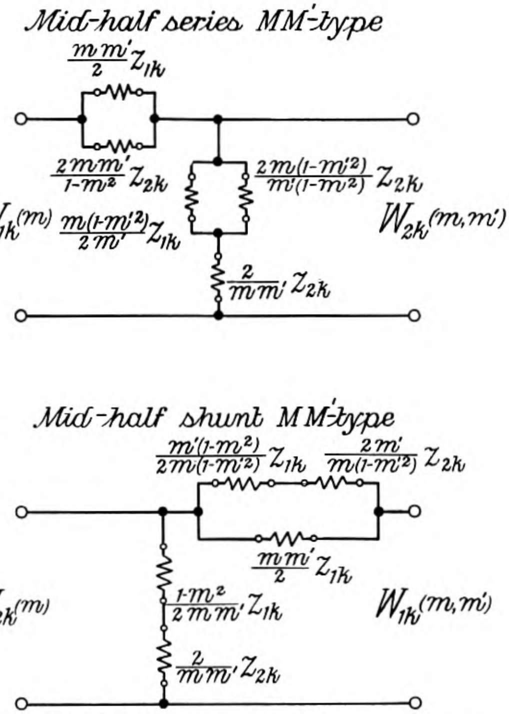


Fig. 8—Mid-half sections of MM'-type wave-filters.

then be described by the following statement. In the range from $U_k = 0$ to -1 the characteristic corresponding to the positive ratio $y = W_{1k}(m, m')/R = R/W_{2k}(m, m')$ may have no maximum or minimum, one maximum, or one maximum and one minimum; at $U_k = 0$, $y = 1$ and at $U_k = -1$, $y = 0$. All of these structures which have the same value of the product $g = mm'$, have the same transfer constant. Thus, it is possible to keep the transfer constant fixed and vary the image impedances.

No structures of any higher order will be worked out here in detail since for all practical purposes the MM'-types just considered will be found capable of meeting the ideal impedance requirements. If desired, the structures for the $MM'M''$-types and higher orders can easily be derived by the regular operations indicated. In them some slight reductions in the number of elements can be made because there are then three or more similar impedances in one branch.

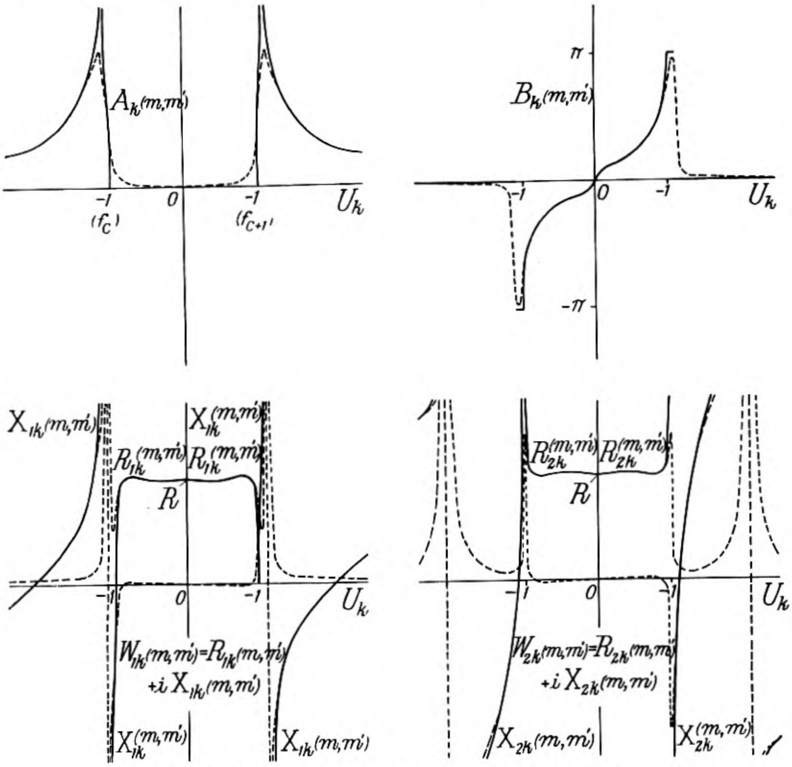


Fig. 9—Characteristics of MM'-type wave-filters;

$m = .7230, \quad m' = .4134.$

($W_{1k}(m)$ and $W_{2k}(m)$ are illustrated in Fig. 7. Broken lines indicate the effects of dissipation.)

It should be quite obvious that a wave-filter of any order reduces to the "constant k" wave-filter when every one of its parameters reaches its limiting value, unity.

1.9 Frequency Relation in the Attenuation Characteristic of an M-Type or Higher Order Wave-Filter of Any Class

The attenuation characteristics of M-type and MM'-type wave-filters which have been illustrated in a limited frequency range show that when dissipation is neglected there is infinite attenuation at some frequency within each branch of x_{1k}. Formula (8), when $V_k = 0$, gives in the attenuating bands where $U_k \leqq -1$

$$\cosh A_k(g) = \left| 1 + \frac{2g^2 U_k}{1 + (1 - g^2) U_k} \right|, \tag{17}$$

in which $g = m, mm', mm'm''$, etc., for the M-types and higher orders. The critical frequencies occur where the attenuation constant becomes zero, i.e., at $U_k = -1$, while the frequencies of infinite attenuation occur where it becomes infinite at $U_k = -1/(1 - g^2)$. Since, when $V_k = 0$, $(z_{1k}/2R)^2 = U_k$, we have the following results:

At critical frequencies f_0, f_1, etc.,

$$z_{1k} = \pm i2R. \tag{18}$$

At frequencies of infinite attenuation, $f_{0\infty}, f_{1\infty}$, etc.,

$$z_{1k} = \pm \frac{i2R}{\sqrt{1 - g^2}}, \tag{19}$$

the number of such frequencies being equal to the number of critical frequencies.

A very simple relation has been found between these two sets of frequencies in the case of any multiple band pass M-type or higher order wave-filter. Such a relation is given here for each of the four general groups into which all classes of band pass wave-filters may be divided, each group having n internal bands with or without low pass and high pass bands.

Group 1.—Low-and-n Band Pass.

$$f_{0\infty} f_{1\infty} \cdots f_{2n\infty} = \frac{1}{\sqrt{1 - g^2}} f_0 f_1 \cdots f_{2n}. \tag{20}$$

Group 2.—n Band-and-High Pass.

$$f_{1\infty} f_{2\infty} \cdots f_{(2n+1)\infty} = \sqrt{1 - g^2} f_1 f_2 \cdots f_{2n+1}. \tag{21}$$

Group 3.—Low-n Band-and-High Pass.

$$f_{0\infty} f_{1\infty} \cdots f_{(2n+1)\infty} = f_0 f_1 \cdots f_{2n+1}. \tag{22}$$

Group 4.—n Band Pass.

$$f_{1\infty} f_{2\infty} \cdots f_{2n\infty} = f_1 f_2 \cdots f_{2n}. \tag{23}$$

For this group there is a further relation but it applies to the impedance characteristics. It contains those frequencies in the transmitting bands where all image impedances become equal to R and where the series impedances belonging to the different orders become resonant. These resonant frequencies f_{1r}, f_{2r}, etc., are the same as those of z_{1k}; that is, where $z_{1k} = 0$. The relation is

$$f_{1r}f_{2r} \cdots f_{nr} = \sqrt{f_1 f_2 \cdots f_{2n}}. \tag{24}$$

It may be noticed that relations (20) and (21) for Groups 1 and 2 are the only ones which depend upon the parameter g. The proofs of all these relations are to be found in Appendix I together with certain reactance frequency theorems.

Part 2. Formation of Terminal Wave-Filter Transducers

2.1 General Design Method

In the Introduction of this paper the method of forming the two general kinds of transducers under consideration has been quite fully discussed. Hence, only a brief repetition will be made here.

The series terminal transducer is designed for connection to the standard mid-series image impedance, W_{1k}, and is formed by connecting in tandem an arbitrary number of single mid-half sections of successively derived structures in Sequence 1, beginning with the series M-type. The image impedances are identical at each junction and adjacent series or shunt impedances can be merged. The number of arbitrary parameters in the final image impedance function is equal to the number of mid-half sections which have been so united. This impedance characteristic is then fixed to give a desired physical result, whence the parameters of all intervening mid-half sections are likewise fixed. The attenuation peaks of successive sections are nearer and nearer the critical frequencies.

The shunt terminal transducer for connection to the standard mid-shunt image impedance, W_{2k}, is designed in a similar manner from the wave-filters of Sequence 2, beginning with the shunt M-type.

From a theoretical standpoint the more mid-half sections used in this composition to obtain a desired constant terminal impedance, the better the possible approximation. The same method of solving for the parameters can be used in all cases. But, in practice, two sections appear to be sufficient.

2.2 Transducers Having Two Parameters

Proceeding on the above basis the two-parameter structures of Fig. 10 are obtained. Their formation will be obvious from Figs.

6 and 8, taking into account the merging of similar impedances at the junctions.

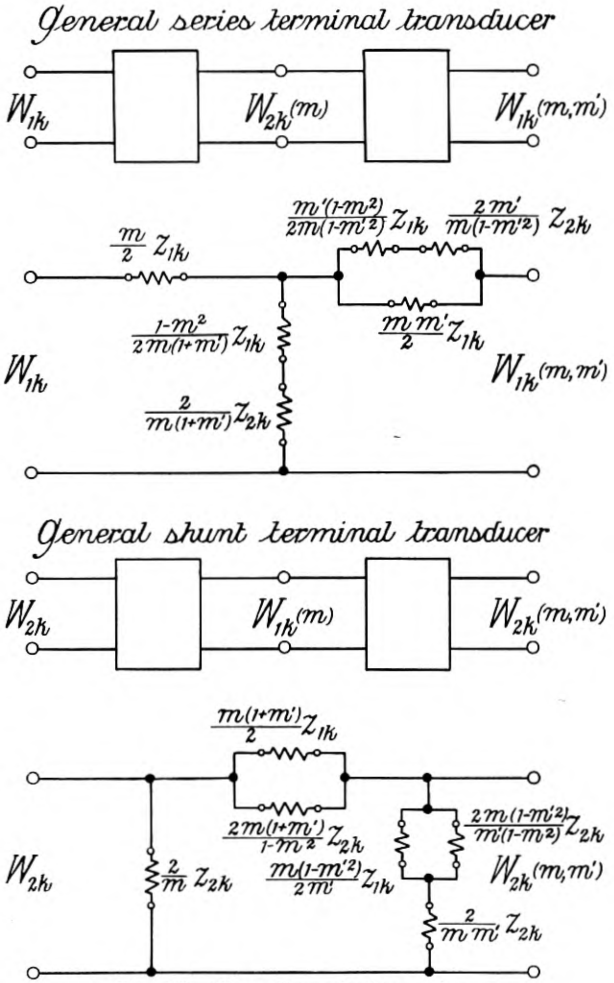


Fig. 10—General terminal transducers.

The transfer constants of both structures are identical being given by

$$T = \tfrac{1}{2}[T_k(m) + T_k(m, m')]. \tag{25}$$

At their initial terminals the image impedances are respectively the standard ones, W_{1k} and W_{2k}, which have the relations

$$\frac{W_{1k}}{R} = \frac{R}{W_{2k}} = \sqrt{1 + U_k + iV_k}; \tag{26}$$

and at their final terminals the image impedance relations are functions of m and m', namely,

$$y = \frac{W_{1k}(m, m')}{R} = \frac{R}{W_{2k}(m, m')} = \frac{[1 + a(U_k + iV_k)]\sqrt{1 + U_k + iV_k}}{[1 + a'(U_k + iV_k)]}, \quad (27)$$

where $a = 1 - m^2$, and $a' = 1 - m^2m'^2$. Since m and m' lie between zero and unity, it follows that $0 \leqq a \leqq a' < 1$.

When there is no dissipation in the network elements, $V_k = 0$ and all these image impedances are pure resistances in all transmitting bands. Then the image impedance ratio y is there real and it can be given a variety of characteristics depending upon the choice of parameters a and a'. For the range $U_k = 0$ to -1, y as a function of U_k may have no maximum or minimum, one maximum, or one maximum and one minimum; at $U_k = 0$, $y = 1$ and at $U_k = -1$, $y = 0$.

The parameters corresponding to any such physical characteristic can be determined from the values of y at two non-zero values of U_k, where now

$$y = \frac{[1 + aU_k]\sqrt{1 + U_k}}{[1 + a'U_k]}.$$

This, when rewritten, yields the general linear equation in a and a'

$$-ua + va' = w, \quad (28)$$

where

$$u = -U_k\sqrt{1 + U_k},$$

$$v = -yU_k,$$

and

$$w = y - \sqrt{1 + U_k}.$$

For generality, let the data be

$$y = y_1 \quad \text{at} \quad (U_k)_1,$$

and

$$y = y_2 \quad \text{at} \quad (U_k)_2.$$

Substitution of these values in (28) gives two simultaneous linear equations in a and a' whose solution is

$$a = \frac{v_1w_2 - v_2w_1}{u_1v_2 - u_2v_1},$$

and

$$a' = \frac{u_1w_2 - u_2w_1}{u_1v_2 - u_2v_1}. \quad (29)$$

Then from (27)

$$m = \sqrt{1 - a},$$

and (30)

$$m' = \sqrt{\frac{1 - a'}{1 - a}}.$$

The maximum and minimum values of y (where $dy/dU_k = 0$) are at the two values of U_k

$$U_k = \frac{-(3a - a') \pm \sqrt{(3a - a')^2 - 4aa'(1 + 2a - 2a')}}{2aa'}. \quad (31)$$

Where it is desired to have an especially constant value, $y = 1$, in the neighborhood of $U_k = 0$, the parameters might be determined from an expansion of the expression for y in powers of U_k. Equating these coefficients of the first and second powers separately to zero would give two independent equations from which to derive the parameters.[12]

2.3 Fixed Designs

The primary interest here is to obtain designs in which the final image impedances are approximately constant resistances equal to R over the entire useful parts of all transmitting bands. Such impedances require a y-characteristic which is close to unity from $U_k = 0$ to the neighborhood of $U_k = -1$. With this objective a few preliminary trials showed that very satisfactory results are obtained with the assumed data

$$y_1 = 1 \quad \text{at} \quad (U_k)_1 = -.65,$$
$$y_2 = 1 \quad \text{at} \quad (U_k)_2 = -.90.$$

Then from (29) and (30) of the previous Section

$$a = .4773, \qquad a' = .9107;$$

and (32)

$$m = .7230, \qquad m' = .4134.$$

These values fix the general structures of Fig. 10, giving the specific ones of Fig. 11 which are made up of definite proportions of the impedances z_{1k} and z_{2k} of the "constant k" wave-filter of that class, assumed known. The detailed y-characteristic of Fig. 12 shows that in this case there is less than a 2 per cent departure of y from the constant value unity over the continuous range from $U_k = 0$ to

[12] A problem of terminal impedance is also included in the paper, "Die Siebschaltungen der Fernmeldetechnik," W. Cauer, *Zeitschrift für Angewandte Mathematik und Mechanik*, October, 1930, p. 425–433.

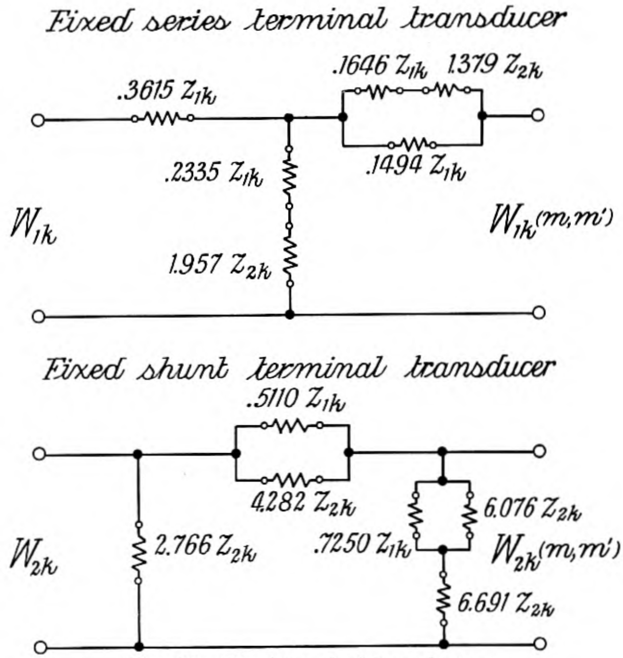


Fig. 11—Fixed terminal transducers;
$m = .7230, \quad m' = .4134.$

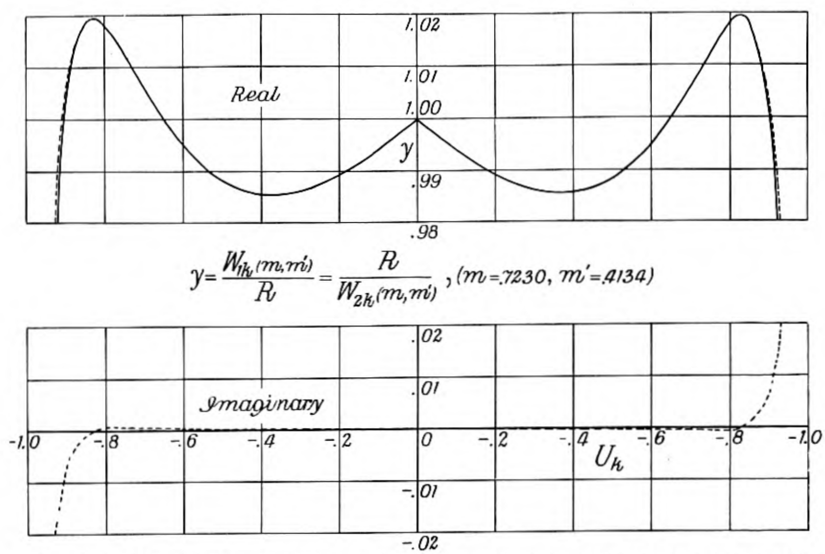


Fig. 12—Detailed terminal image impedance characteristics in the transmitting bands of fixed terminal transducers.

(Broken lines are for dissipation with $V_k = \pm .01\, U_k$).

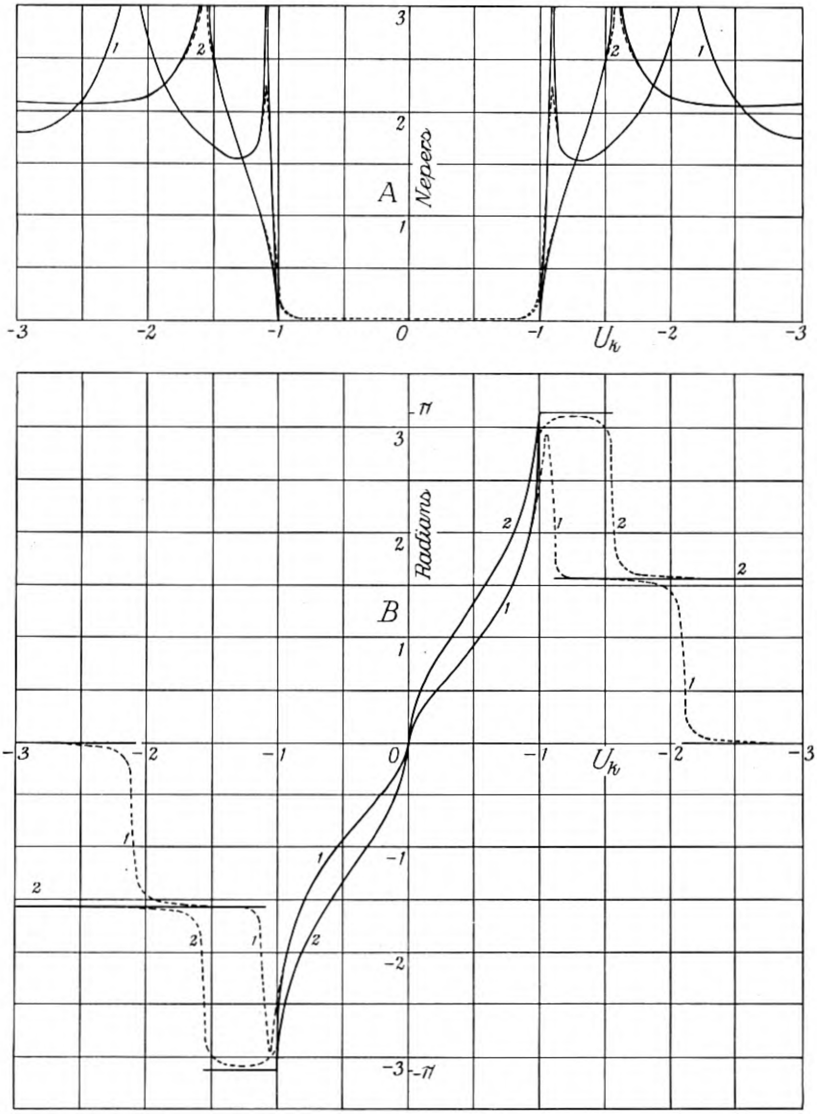


Fig. 13—Transfer constants ($T = A + iB$)—

(1) of fixed terminal transducers,
(2) of comparison transducers.

(A comparison transducer consists of one mid-half section of the "constant k" wave-filter and one of either M-type, where $m = .6$. Broken lines are for dissipation with $V_k = \pm .01 U_k$).

$U_k = -.92$ in every branch, which range includes the useful part of a branch. In low pass and band pass wave-filters this total range corresponds to 96 per cent of the theoretical band widths. From (31) there is a minimum $y = .9857$ at $U_k = -.3696$, and a maximum $y = 1.0198$ at $U_k = -.8297$. Of course, other values of the parameters in this neighborhood would also be quite satisfactory. They might even be fixed by choosing the frequencies of infinite attenuation in the two half sections. But the above were taken in order to fix the final networks.

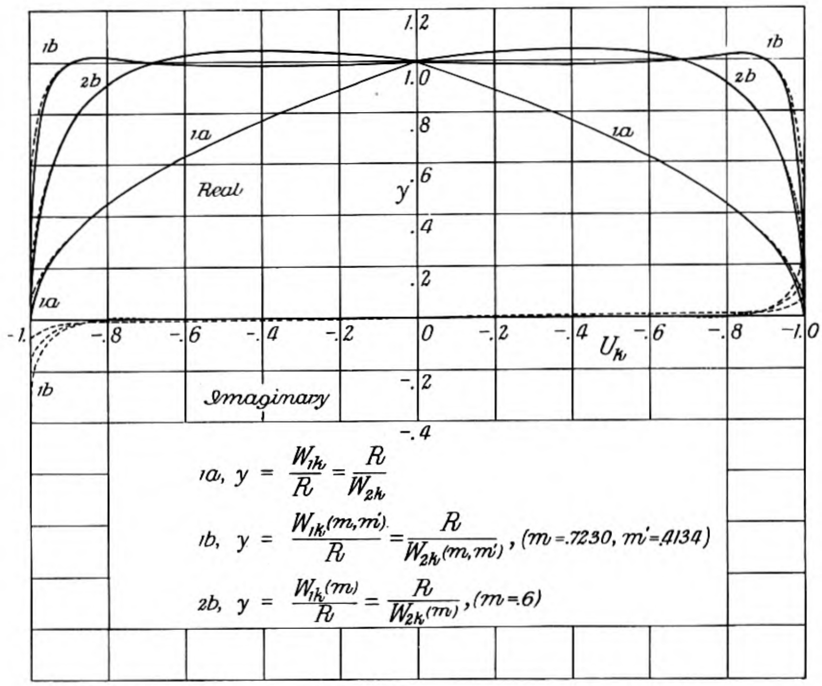


Fig. 14—Image impedance characteristics in the transmitting bands—
($1a$, $1b$) of fixed terminal transducers,
($1a$, $2b$) of comparison transducers.
(Broken lines are for dissipation with $V_k = \pm .01\, U_k$).

The transfer constants of these fixed terminal transducers of Fig. 11 are represented by the general attenuation and phase characteristics of Fig. 13. Here also are shown the corresponding characteristics of two comparison transducers, one of which is made up of a mid-half section each of the "constant k" and of the shunt M-type wave-filters and has the image impedances W_{1k} and $W_{1k}(m)$. The other, made up similarly, has the image impedances W_{2k} and $W_{2k}(m)$. In both comparison transducers $m = .6$, this value of the parameter giving results which are representative of the best constant terminal impedances possible in transducers with terminal M-types. (These comparison networks are identical with the general ones of Fig. 10 in which $m = 1$ and $m' = .6$.) Corresponding image impedance ratios in a transmitting band are given in Fig. 14 where curves 1*a* and 1*b* are characteristics for the two ends of the new terminal transducers of Fig. 11, while curves 1*a* and 2*b* are those of the comparison networks. The superior merits of the new transducers can be seen from Figs. 13 and 14; for in addition to giving improved and practically ideal terminal impedances they have attenuation characteristics just outside the transmitting bands which rise more rapidly than those of the comparison transducers.

By the use of such and other fixed terminal transducers at one or both ends of a wave-filter network, the flexibility of the composite method of designing wave-filters is still retained. The transducer transfer constants and terminal losses due to reflection at given terminating impedances are known in advance. The interior of the composite wave-filter can then be built up of ladder, lattice or other types of sections so that the desired total transmission characteristic is obtained. Constant resistance phase networks can also be added at a resistance termination to help improve the phase characteristic in the transmitting bands, if necessary.

2.4 Designs for Low Pass, High Pass, Low-and-High Pass and Band Pass Wave-Filters

These fixed transducers of Fig. 11 may readily be translated into the particular designs which they assume for any class of wave-filter with z_{1k} and z_{2k} known. For low pass, high pass, low-and-high pass and band pass wave-filters, the four most important classes, the actual physical arrangements and formulas for the inductances and capacities have been worked out. As a convenience in reference these designs are placed in Appendix II where all necessary formulas are given, making use of Appendix II of the paper mentioned in footnote 1. Little further discussion will be given here except to add the relations between U_k and frequency for these different classes, with dissipation neglected. By this means the characteristics which have been shown as functions of U_k may be referred to the frequency scale as the abscissa-axis, if desired in any particular case.

I.—Low Pass

$$U_k = -\left(\frac{f}{f_0}\right)^2, \tag{33}$$

and x_{1k} is made up of one positive branch.

II.—High Pass

$$U_k = -\left(\frac{f_1}{f}\right)^2, \tag{34}$$

and x_{1k} consists of one negative branch.

III.—Low-and-High Pass

$$U_k = -\frac{(f_1 - f_0)^2}{f_0 f_1} \frac{1}{\left(\frac{f_{1a}}{f} - \frac{f}{f_{1a}}\right)^2}, \tag{35}$$

where $f_{1a} = \sqrt{f_0 f_1}$, the anti-resonant frequency where $U_k = \infty$ and $x_{1k} = \infty$. For this class x_{1k} has a positive branch from 0 to f_{1a} and a negative branch from f_{1a} to ∞.

IV.—Band Pass

$$U_k = -\frac{f_1 f_2}{(f_2 - f_1)^2}\left(\frac{f_{1r}}{f} - \frac{f}{f_{1r}}\right)^2, \tag{36}$$

where $f_{1r} = \sqrt{f_1 f_2}$, the mid-frequency or resonant frequency where $U_k = 0$ and $x_{1k} = 0$. Here x_{1k} is made up of a negative branch in the frequency range from 0 to f_{1r} and a positive branch from f_{1r} to ∞.

2.5 *Equivalent Structures*

Many structures can be obtained which are externally equivalent to each of the above transducers; in fact, an infinite number is possible. That this is so can be seen from a consideration of the general transducers of Fig. 11, for example. It will not even be necessary to include the entire networks in this discussion but only the branches containing three impedances of two kinds, z_{1k} and z_{2k}. The branch containing one of z_{1k} in parallel with the series combination of one of z_{1k} and one of z_{2k} may be transformed completely by a well-known formula into one of z_{1k} in series with a parallel combination of one of z_{1k} and one of z_{2k}. No change in the number of impedance elements results and the magnitudes are fixed. If, however, an arbitrary part of the original parallel z_{1k} branch is kept out of the above transformation the final equivalent structure would have one more z_{1k} impedance and one more mesh than the original. The proportions of each impedance may obviously be varied continuously as the arbitrary division is so varied, thereby giving an infinite variety of magnitudes. This four impedance structure, equivalent to the original one, reduces at the limits to the two structures each having three fixed impedances, as we know. A similar process can be carried out with the shunt branch in the shunt transducer which contains three impedances. In this case the series z_{2k} impedance of this branch would be arbitrarily divided and one part transformed by another well-known transformation with the parallel branch in series with it. The final result would be a z_{2k} in series with a parallel combination of a z_{2k} and series z_{1k} and z_{2k}; that is, four impedances but no additional mesh. Here again the magnitudes would have a continuous range but at the limits with three impedances they are fixed. Other methods of transformations can be used on the network as a whole and most of the equivalents have more elements.

As a matter of interest a number of equivalents of the networks of Fig. 11 will be pointed out, all of which have the same minimum number of impedances. Starting with the transformations mentioned above, the latter series transducer has a star of z_{1k} impedances which may be transformed into a delta, thereby adding another mesh. Similarly the latter shunt transducer has a delta of z_{2k} impedances which may be given the form of a star which eliminates a mesh. Two other forms are given as V_1 and V_2 in Appendix II, being respectively equivalent to the series and shunt transducers. They are inverse networks just as are the originals in Fig. 11. In V_1 a still further transformation can be made from a star to a delta of z_{1k} impedances; in V_2 from a delta to a star of z_{2k} impedances. The possibility of obtaining the particular forms V_1 and V_2 was pointed out by H. W. Bode. I have derived them directly from the networks of Fig. 11 by a transformation of the major part of each network, using the simple formulas for the equivalent transducer transformations, respectively 1 and 2, of Appendix III.

The transformation formulas for these latter equivalent transducers in Appendix III are readily verified by the ordinary transformations from T to π networks, and vice versa.

In the higher class wave-filters which contain more than one element in z_{1k} and z_{2k}, transformations of only parts of z_{1k} and z_{2k} are also possible. For various other kinds of transformations see footnote 16 to Appendix III.

2.6 Terminal Losses at MM′-Type Terminations

When the terminal image impedance of a wave-filter is $W_{1k}(m, m')$ or $W_{2k}(m, m')$ and the wave-filter is terminated by a resistance R, there is a reflection loss at the junction due to the impedance irregularity which will be called the terminal loss $L_{m,m'}$. It is defined by the relations

$$e^{L_{m,m'}} = \left| \frac{R + W_{1k}(m, m')}{2\sqrt{RW_{1k}(m, m')}} \right| = \left| \frac{R + W_{2k}(m, m')}{2\sqrt{RW_{2k}(m, m')}} \right| \qquad (37)$$

which are exactly analogous to formulas (33) and (34) of the paper cited here in footnote 2. Thus $L_{m,m'}$ may be plotted so as to give an additional chart for use in the method of calculating wave-filter transmission losses considered in that paper, which will apply when there are these kinds of MM'-type terminations. As a convenience a chart for $L_{m,m'}$ is given in Appendix IV for the particular values of the parameters $m = .7230$ and $m' = .4134$ already chosen in the fixed terminal transducers. To take account of dissipation several curves are shown for each one of which there is a different fixed relation between V_k and U_k. This chart, being an extension to the former set of charts, is numbered consecutively with the others as Chart 20. It shows that the terminal loss at R has two maxima beyond each critical frequency where $U_k = -1$. Their locations correspond to one resonant and one anti-resonant point of $W_{1k}(m, m')$ or $W_{2k}(m, m')$ in an attenuating band. Moreover, the position of the first and lowest maximum coincides with that of the maximum attenuation of the terminating wave-filter, the MM'-type, while the position of the second coincides with that of the maximum attenuation of the related M-type. (An M-type termination gives only the first maximum; an $MM'M''$-type gives three maxima, etc.) The transmission unit, the Neper, is the same as that which was called the *attenuation unit* on the previous charts. The corresponding number of decibels is obtained by multiplying the number of Nepers by 8.686.

When such a termination is used the interaction loss is practically negligible.

Part 3. Simulation of Wave-Filter Impedances

So far the two networks of Fig. 11 have been considered only from the standpoint of their use as terminal wave-filter transducers with desirable propagation and image impedance characteristics. While this is their major purpose they can have a minor use to be shown here, namely, as parts of two-terminal networks whose purpose is to simulate wave-filter impedances where such networks may be desired. This possibility is suggested by the fact that the image impedances at the final terminals are approximately equal to a constant resistance in all transmitting bands which can be simulated at these frequencies by a simple resistance R. It follows that if each pair of final terminals is terminated by a resistance R, the impedances at the two remaining pairs of terminals will be approximately equal to their image impedances, W_{1k} and W_{2k}, respectively, in the transmitting bands. Moreover, on account of the high attenuation of the transducers in the attenuating bands which reduces transmission through them, the large impedance irregularities at those frequencies between each network and its terminating resistance R will produce only a small effect upon the impedances at the other terminals. As a result the latter impedances will be approximately equal to W_{1k} and W_{2k} in the attenuating bands also. Higher order transducers might also be used.[13]

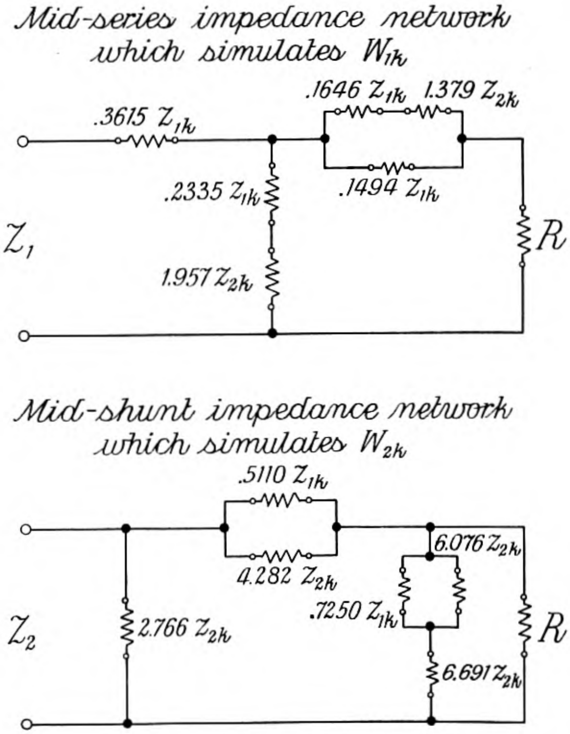


Fig. 15—Impedance networks which simulate the image impedances, W_{1k} and W_{2k}, of "constant k" and related wave-filters of any class.

With this explanation of their origin the general impedance networks of Fig. 15 have been assembled. One of impedance Z_1 simulates the image impedance W_{1k}; the other of impedance Z_2, the image impedance W_{2k}. The degree of simulation attained can be seen from the characteristics of Fig. 16, wherein the effect of small dissipation is included by assuming $V_k = + .01\,U_k$ in a negative branch and $V_k = - .01\,U_k$ in a positive branch, as before. Over most of a transmitting band the agreement is within a few per cent; outside it is still quite satisfactory. Near the critical frequencies, where

[13] Still other forms of networks have been considered by R. Feldtkeller in a paper "Über einige Endnetzwerke von Kettenleitern," *Elektrische Nachrichten-Technik*, Band 4, Heft 6, p. 253, 1927.

$U_k = -1$, the simulation is improved by dissipation, as we might expect.

This physical possibility of closely simulating the image impedance of a wave-filter shows that the assumption of such a physical termination, as made in a previous paper,[14] was practically justified when solving the problem of the behavior of wave-filters under non steady-state conditions.

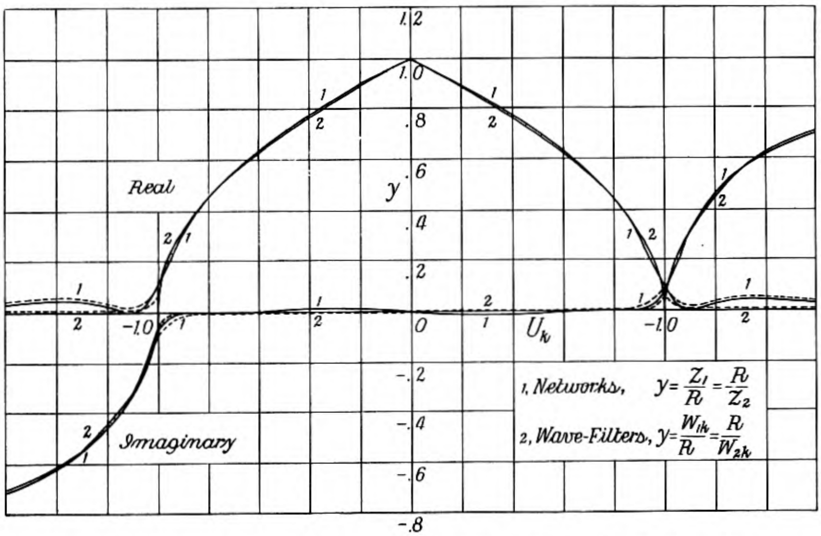


Fig. 16—Simulation of the image impedances W_{1k} and W_{2k} by the impedance networks of Fig. 15. (Broken lines are for dissipation with $V_k = \pm .01 U_k$).

The particular structures for simulating the impedances of "constant k" low pass, high pass, low-and-high pass and band pass wave-filters, which correspond to the general ones of Fig. 15, are obtained by terminating the networks of Appendix II with resistances R. It is understood, of course, that others than the "constant k" wave-filter of any class have either the image impedance W_{1k} or W_{2k}. Obviously, it would be possible to simulate the impedance of any wave-filter which by proper combination on the image basis can be linked with these networks simulating W_{1k} or W_{2k}. This, therefore, gives a method for obtaining in a limited frequency range or ranges almost any resistance characteristic with zero reactance.

Likewise, the impedance of a mid-series section of the shunt MM'-type or a mid-shunt section of the series MM'-type which has the parameters of formula (32) and one pair of its terminals closed by a

[14] "Transient Oscillations in Electric Wave-Filters," J. R. Carson and O. J. Zobel, *B. S. T. J.*, July, 1923.

resistance R, is a good simulation of $W_{1k}(m, m')$ or $W_{2k}(m, m')$. The latter are, as we know, approximately constant resistances equal to R over desired frequency ranges and are reactances at other frequencies. An interesting use of either or both of these simulating networks would be as a balancing network against a resistance R or against each other in a hybrid set. At frequencies in those ranges where the balance is quite accurate, currents in the main circuit would be highly attenuated, these attenuating bands corresponding to the transmitting bands of the wave-filter impedance section.

PART 4. SIMULATION OF LOADED LINE IMPEDANCES

The networks of Fig. 17 are capable of giving impedance simulation over the greater part of the principal transmitting band of a

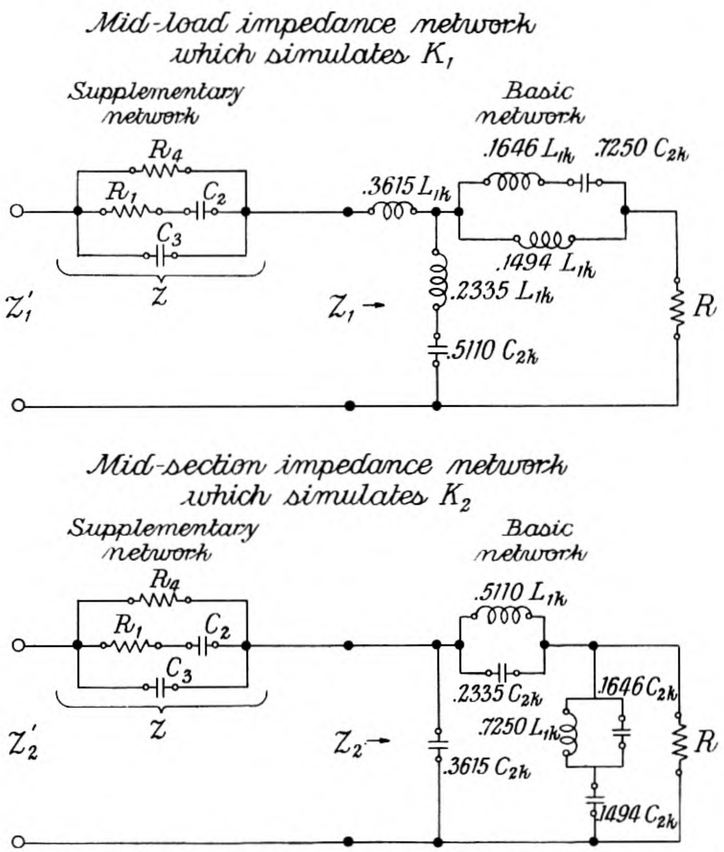


Fig. 17—Impedance networks which simulate the iterative impedances, K_1 and K_2, of a loaded line at mid-load and mid-section terminations, respectively.

loaded line. They are useful in cases where it is desirable to extend nearer the critical frequency the range of simulation possible by means of the networks described by R. S. Hoyt.[15]

Designs are given for mid-load and mid-section terminations. Results for other terminations can be obtained by building out the load or section. From an economic standpoint it might be pointed out that the basic networks for the mid-point impedances to be described each have seven elements, whereas corresponding designs based upon Figs. 14 and 15 of Hoyt's paper would have six elements. However, the new mid-load basic network which extends the range of simulation requires only one-half the total amount of capacity but slightly more inductance than that required by the corresponding Hoyt network; the new mid-section basic network requires only one-half the total amount of inductance but slightly more capacity than the corresponding Hoyt network.

4.1 Foundation of Designs

The design of any simulating network usually involves two processes, namely, a determination first of structural form and second of magnitudes.

The structural forms of the new designs follow readily from the well-justified assumption that either mid-point impedance of a loaded line in its principal transmitting band is approximately equal to the corresponding mid-point impedance of a "constant k" low pass wave-filter as the basic network, with the series addition of the impedance of a supplementary network which simulates the additional impedance introduced by dissipation at low frequencies. While this assumption is really the same one which underlies the designs by Hoyt, the new basic networks have considerably different forms and were derived from wave-filter theory, which explains their inclusion in this paper. In fact, the desired basic networks of Fig. 17 are immediately available from the results of Part 3, being special cases of the networks of Fig. 15 which use the low pass wave-filters of Appendix II.

The particular supplementary network chosen, one already considered by Hoyt but designed differently, has four elements, two resistances and two capacities, and is known to have the desired impedance characteristic. The same one will generally do for either mid-load or mid-section impedance, as it contributes impedance only at the lower frequencies of the range.

The magnitudes of the elements of these networks are all determined

[15] "Impedance of Loaded Lines, and Design of Simulating and Compensating Networks," R. S. Hoyt, *B. S. T. J.*, July, 1924.

from computed loaded line impedances (or perhaps from measured impedances), instead of directly from certain primary line and coil data. This makes it comparatively easy to take account of variations with frequency of the constants, such as line leakance and loading coil resistance.

The mid-load iterative impedance is given by the formula

$$K_1 = k\sqrt{\left(1 + \frac{z_L}{2k}\tanh\frac{S\gamma}{2}\right)\left(1 + \frac{z_L}{2k}\coth\frac{S\gamma}{2}\right)}; \qquad (38)$$

the mid-section iterative impedance by

$$K_2 = k\sqrt{\frac{1 + \frac{z_L}{2k}\coth\frac{S\gamma}{2}}{1 + \frac{z_L}{2k}\tanh\frac{S\gamma}{2}}}. \qquad (39)$$

In these formulas γ and k are the propagation constant and iterative impedance, respectively, of the non-loaded line which may be computed on the basis that the shunt capacity of each loading coil and its leads is assumed to be concentrated, half at each end, and that each half is added in the formulas to the line capacity of the adjacent section. S is the load spacing and z_L the load impedance.

4.2 Mid-Load Basic Network

This basic network has the structure and general design shown in the upper part of Fig. 17. The magnitudes of its elements are fixed when R and f_0 are known, since

$$L_{1k} = R/\pi f_0,$$

and

$$C_{2k} = 1/\pi f_0 R; \qquad (40)$$

where R is the impedance $\sqrt{L_{1k}/C_{2k}}$ and f_0 is the critical frequency. Its impedance in the frequency range considered is quite accurately given by

$$Z_1 \approx R\sqrt{1 - \left(\frac{f}{f_0}\right)^2} = r, \qquad (41)$$

which relation will be used for design purposes. The values of R and f_0 are here determined for any particular loaded line by assuming that at two frequencies, f_a and f_b, the corresponding values of r, respectively r_a and r_b, are equal to the resistance components of K_1 as computed at those frequencies from (38). The frequencies f_a and f_b are chosen in the upper part of the desired range where the reactance components of K_1 are small. Substitution of these values in (41) gives two linear equations in R^{-2} and f_0^{-2} from which

$$R = r_a \sqrt{\frac{1 - \left(\frac{f_a r_b}{f_b r_a}\right)^2}{1 - \left(\frac{f_a}{f_b}\right)^2}},$$

and (42)

$$f_0 = f_b \sqrt{\frac{1 - \left(\frac{f_a r_b}{f_b r_a}\right)^2}{1 - \left(\frac{r_b}{r_a}\right)^2}}.$$

The actual impedance, Z_1, of the network with these values may be computed as for any finite network.

4.3 Mid-Section Basic Network

This network in the lower part of Fig. 17 is the mid-shunt simulating network corresponding to Fig. 15.

Its impedance in the desired range is approximately given by the formula

$$Z_2 \approx \frac{R}{\sqrt{1 - \left(\frac{f}{f_0}\right)^2}} = r. \tag{43}$$

To determine R and f_0, assume two values of r to be equal to r_a and r_b, the resistance components of K_2 as computed from (39) at two frequencies f_a and f_b, where the reactance components of K_2 are small. Then from (43) we obtain two linear equations in R^2 and f_0^{-2} from which

$$R = r_a \sqrt{\frac{1 - \left(\frac{f_a}{f_b}\right)^2}{1 - \left(\frac{f_a r_a}{f_b r_b}\right)^2}},$$

and (44)

$$f_0 = f_b \sqrt{\frac{1 - \left(\frac{f_a r_a}{f_b r_b}\right)^2}{1 - \left(\frac{r_a}{r_b}\right)^2}}.$$

The actual impedance of this network is Z_2. The values of R and f_0 from (44) will be practically the same as those from (42).

4.4 Supplementary Network

Shown in both simulating networks of Fig. 17, this network has an impedance expression of the form

$$z = \frac{a_0 + a_1 if}{1 + b_1 if - b_2 f^2} = r + ix, \qquad (45)$$

where

$$a_0 = R_4,$$
$$a_1 = 2\pi R_1 R_4 C_2,$$
$$b_1 = 2\pi(R_1 C_2 + R_4 C_2 + R_4 C_3),$$

and

$$b_2 = 4\pi^2 R_1 R_4 C_2 C_3.$$

The resistance and capacity elements are obtained from the above impedance coefficients as

$$R_1 = a_0 a_1^2/(a_0 a_1 b_1 - a_0^2 b_2 - a_1^2),$$
$$C_2 = (a_0 a_1 b_1 - a_0^2 b_2 - a_1^2)/2\pi a_0^2 a_1,$$
$$C_3 = b_2/2\pi a_1, \qquad (46)$$

and

$$R_4 = a_0.$$

From (45) the pair of *impedance linear equations* is

$$a_0 + fxb_1 + f^2 rb_2 = r,$$

and

$$fa_1 - frb_1 + f^2 xb_2 = x. \qquad (47)$$

With the above formulas we can proceed to indicate the method of design.

Ideally the network should have the impedance characteristic

$$z = r + ix = K_1 - Z_1, \qquad (48)$$

or

$$z = r + ix = K_2 - Z_2, \qquad (49)$$

depending upon which mid-point impedance, K_1 or K_2, is being simulated. Usually these two values of z are practically the same. To fix the four impedance coefficients, assume that the network has the ideal components of (48) or (49) at two important low frequencies, the data with increasing frequency being,

$$f_1, \quad r_1 + ix_1;$$

and

$$f_2, \quad r_2 + ix_2.$$

These values are to be substituted in (47) to obtain four linear equations. The solution of these linear equations gives

$$
\begin{aligned}
a_0 &= r_1 - f_1x_1b_1 - f_1^2r_1b_2, \\
a_1 &= r_1b_1 - f_1x_1b_2 + x_1/f_1, \\
b_1 &= \frac{f_1f_2(f_1x_1 - f_2x_2)(r_1 - r_2) + (f_1x_2 - f_2x_1)(f_1^2r_1 - f_2^2r_2)}{D}, \\
b_2 &= \frac{f_1f_2(r_1 - r_2)^2 + (f_1x_1 - f_2x_2)(f_2x_1 - f_1x_2)}{D},
\end{aligned} \tag{50}
$$

where

$$D = f_1f_2\left\{(f_1^2r_1 - f_2^2r_2)(r_1 - r_2) + (f_1x_1 - f_2x_2)^2\right\}.$$

From the values of a_0, a_1, b_1, and b_2 the network constants can be computed by formulas (46). The network impedance is then given at any frequency by formula (45).

The actual impedance simulating K_1 is the sum, $Z_1' = Z_1 + z$; that simulating K_2 is the sum, $Z_2' = Z_2 + z$.

It should be pointed out here that the supplementary network may, if desired, be given other structural forms having two resistances and two capacities and having an equivalent impedance characteristic. These other forms may be obtained by transformations from the known one above or their elements determined from other formulas corresponding to those of (46).

Likewise, a supplementary network which has a smaller or larger number of elements than the one above might be used satisfactorily with the same basic networks or their equivalents. That depends upon the low-frequency impedance characteristics of the given loaded line and upon the closeness of simulation desired.

4.5 *Application of Results*

To illustrate the possibilities of these impedance networks, mid-load and mid-section designs are given here for a 19-gauge B-88–50 loaded side-circuit. The "B" spacing is $S = .568$ mile (3000 feet).

Data for the mid-load basic network, taken from computations of K_1, are

$$f_a = 3000, \qquad r_a = 1324;$$

and

$$f_b = 5000, \qquad r_b = 720.$$

These give from (42), $R = 1564.4$ ohms, and $f_0 = 5632$ cycles per second.

Data for the mid-section basic network, taken from computations of K_2, are

$$f_a = 3000, \qquad r_a = 1848;$$

and

$$f_b = 5000, \qquad r_b = 3387.$$

Then from (44), $R = 1564.6$ ohms, and $f_0 = 5638$ cycles per second. Because of the close agreement between these two sets of results, their approximate mean values will here be used in both basic networks, namely

$$R = 1565 \text{ ohms},$$

and

$$f_0 = 5635 \text{ cycles per second.}$$

With these values in (40), $L_{1k} = 88.38$ mh., and $C_{2k} = .03611$ mf. We have then for the *mid-load basic network* the inductance and capacity elements:

$$.3615\ L_{1k} = 31.95 \text{ mh.}; \qquad .2335\ L_{1k} = 20.64 \text{ mh.};$$
$$.1646\ L_{1k} = 14.55 \text{ mh.}; \qquad .1494\ L_{1k} = 13.20 \text{ mh.};$$
$$.5110\ C_{2k} = .01845 \text{ mf.}; \qquad .7250\ C_{2k} = .02618 \text{ mf.};$$

and for the *mid-section basic network*

$$.5110\ L_{1k} = 45.16 \text{ mh.}; \qquad .7250\ L_{1k} = 64.08 \text{ mh.};$$
$$.3615\ C_{2k} = .01305 \text{ mf.}; \qquad .2335\ C_{2k} = .008431 \text{ mf.};$$
$$.1646\ C_{2k} = .005943 \text{ mf.}; \qquad .1494\ C_{2k} = .005395 \text{ mf.};$$

with their locations as in Fig. 17.

The impedance characteristics of these basic networks, Z_1 and Z_2, were computed directly from the finite networks on the assumption of small coil and condenser dissipation constants, $d = d' = .005$. Comparatively small reactance components begin to appear above 4500 cycles per second. Increasing the amount of dissipation in the reactance elements would tend to increase the reactance components of Z_1 and Z_2 at the upper frequencies.

The design of the single supplementary network was made from low frequency data representing the average values of $(K_1 - Z_1)$ and $(K_2 - Z_2)$. The data are

$$f_1 = 100, \qquad r_1 + ix_1 = 152 - i700,$$

and

$$f_2 = 300, \qquad r_2 + ix_2 = 20 - i252.$$

From formulas (50) we obtain

$$a_0 = 7839.0; \qquad a_1 = 233.12;$$
$$b_1 = 17.600 \cdot 10^{-2}; \qquad b_2 = 30.481 \cdot 10^{-4}.$$

From (46) these give

$$R_1 = 5327 \text{ ohms}; \qquad C_2 = .8886 \text{ mf.};$$
$$C_3 = 2.081 \text{ mf.}; \qquad R_4 = 7839 \text{ ohms}.$$

The impedance characteristic above 100 cycles per second as computed from formula (45) is mostly that of negative reactance, both components decreasing rapidly with frequency.

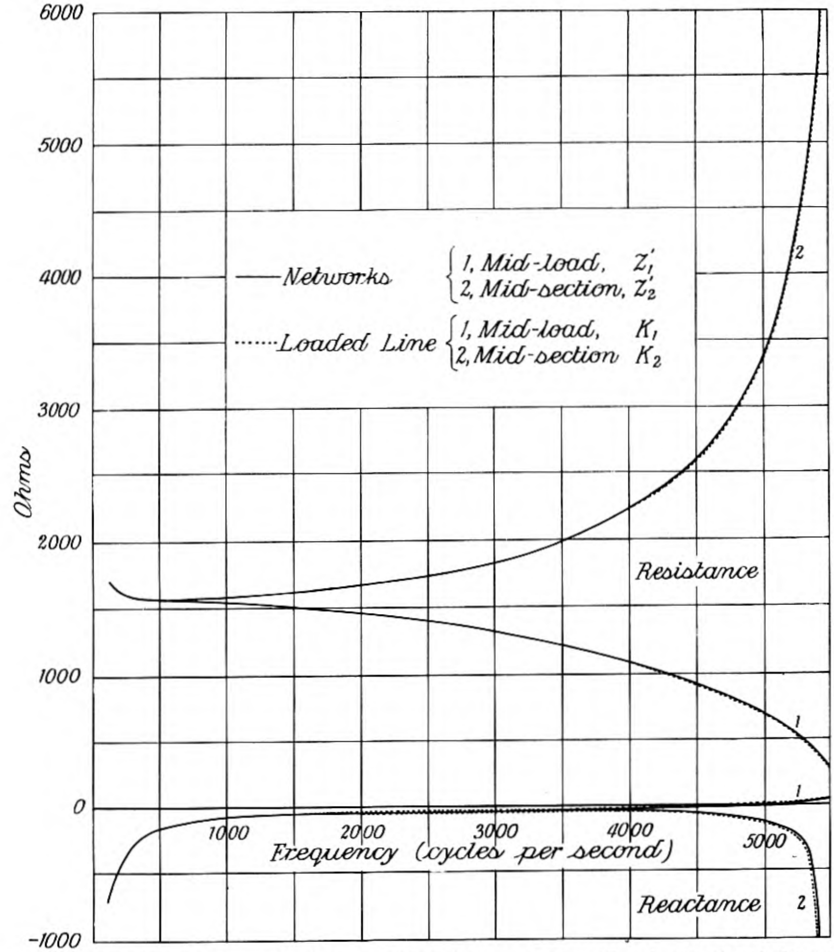


Fig. 18—Simulation of the iterative impedances, K_1 and K_2, of a 19-Ga. B-88-50 loaded side-circuit by the impedance networks of Fig. 17. (Coil and condenser dissipation constants are $d = d' = .005$.)

Final results showing the characteristics of the complete simulating networks are compared with those of the loaded line in Fig. 18.

Simulation is within .7 per cent of the impedance over the continuous range from 100 to 3000, within 2 per cent from 3000 to 5000, and within 4 per cent from 5000 to 5500 cycles per second; the per cent accuracy is best in the case of the mid-section network. This upper frequency is approximately 97 per cent of the critical frequency, 5635 cycles per second. There is good simulation even considerably beyond the critical frequency, as may be inferred from Fig. 16.

For still greater precision, networks which originally have three or more parameters and which are formed in a manner similar to those of Fig. 15 may constitute the basic networks.

4.6 Other Approximate Designs

Alternative designs of networks simulating K_1 and K_2 can be made with the networks of Fig. 15 as foundations. The method of doing this will merely be outlined here since the networks do not appear to be as practical as the ones already described in detail.

This procedure assumes that the actual loaded line structure can be quite accurately represented physically in the desired frequency range by a ladder structure of series and shunt impedances, z_1 and z_2, respectively. Roughly, z_1 would be series resistance and inductance and z_2 would be parallel resistance and capacity. Then throughout the two networks of Fig. 15 the impedance of z_{1k} is to be replaced by that of z_1 and the impedance of z_{2k} by that of z_2. Also the terminating resistance R is to be replaced by $\sqrt{z_1 z_2}$, the impedance of the corresponding uniform line, which in this case might be approximately simulated by a resistance in series with a network like the supplementary network of Fig. 17. The resulting impedance networks would then approximately represent K_1 and K_2. However, no design formulas are needed to show that even if these networks give as good simulation as the networks of Fig. 17 they would require more elements.

Appendix I

Reactance Frequency Theorems and Proofs of Frequency Relations in M-Type or Higher Order Wave-Filters

There are certain simple frequency relations which hold in the reactance characteristics of non-dissipative impedances. A statement and proof of these relations will first be given. From them will follow readily the proofs of the frequency relations in the characteristics of M-type or higher order wave-filters, which are represented by formulas (20) to (24), since they require a consideration of the "constant k" series impedance z_{1k} only.

Reactive Impedance Characteristics

All non-dissipative impedances have reactances which can be separated into four forms of impedance functions, each of which can be expressed as the ratio of two frequency-polynomials in if, where $i = \sqrt{-1}$, and f is frequency. It is known that such a reactance necessarily has a positive slope with frequency and hence the resonant and anti-resonant frequencies alternate on the frequency scale. The four mathematical forms may be separated on the basis of the general location of their resonant frequencies and have finite resonant frequencies with or without zero and infinite resonant frequencies. These reactive impedance forms are as follows:

Form 1. Resonant at zero and n finite frequencies.

$$z = \frac{a_1 if + a_3(if)^3 + \cdots + a_{2n+1}(if)^{2n+1}}{1 + b_2(if)^2 + \cdots + b_{2n}(if)^{2n}} = ix. \tag{51}$$

Form 2. Resonant at n finite and infinite frequencies.

$$z = \frac{1 + a_2(if)^2 + \cdots + a_{2n}(if)^{2n}}{b_1 if + b_3(if)^3 + \cdots + b_{2n+1}(if)^{2n+1}} = ix. \tag{52}$$

Form 3. Resonant at zero, n finite and infinite frequencies.

$$z = \frac{a_1 if + a_3(if)^3 + \cdots + a_{2n+1}(if)^{2n+1}}{1 + b_2(if)^2 + \cdots + b_{2n+2}(if)^{2n+2}} = ix. \tag{53}$$

Form 4. Resonant at n finite frequencies.

$$z = \frac{1 + a_2(if)^2 + \cdots + a_{2n}(if)^{2n}}{b_1 if + b_3(if)^3 + \cdots + b_{2n-1}(if)^{2n-1}} = ix. \tag{54}$$

Each of these forms has a simple frequency relation which is expressible as a theorem.

Reactance Frequency Theorems

The product F of the frequencies at which the reactance x is $\pm c$ in each of the four reactive impedance forms is the following:

Form 1. $F_{2n+1} = \dfrac{c}{a_{2n+1}}$, *proportional to c.*

Form 2. $F_{2n+1} = \dfrac{1}{cb_{2n+1}}$, *inversely proportional to c.*

Form 3. $F_{2n+2} = \dfrac{1}{b_{2n+2}}$, *independent of c.*

When $c = \infty$, meaning anti-resonance of z, each anti-resonant frequency appears twice in the product.

Form 4. $$F_{2n} = \frac{1}{a_{2n}}, \text{ independent of } c.$$

When $c = 0$, meaning resonance of z, each resonant frequency appears twice in the product.

To prove the theorem for Form 1 first square the expression in (51) and clear the fraction. This gives a polynomial in f^2 of degree $2n + 1$, of which only the terms of highest and zero powers need be shown for our purpose. Thus

$$(f^2)^{2n+1} + \cdots - \frac{x^2}{a_{2n+1}^2} = 0, \tag{55}$$

which expresses the general relationship between x^2 and f^2. If x^2 is given some constant value as $x^2 = c^2$, that is $x = \pm c$, the roots of (55) will be the $2n + 1$ distinct values of f^2 where $x = \pm c$. By the theory of equations, the product of these $2n + 1$ values of f^2 is (c^2/a_{2n+1}^2). Since we are interested only in positive frequencies, we may take the positive square root of both sides with the result that the product of all frequencies at which $x = \pm c$ is c/a_{2n+1}, which proves the theorem.

The proofs of the theorems for Forms 2, 3 and 4 are exactly similar and should not need further explanation. In Form 3 the values $x = \pm \infty$ occur at the anti-resonant frequencies of z, namely f_{1a}, f_{2a}, etc.; hence, when $c = \infty$ the total frequency product includes each of the latter frequencies twice. The result for Form 4 has a meaning even at the limit $c = 0$. These frequencies are the resonant ones of z, where $z = 0$, and each one of them must obviously appear twice in the total product.

Proofs of Wave-Filter Frequency Relations

As was stated in Section 1.9, z_{1k} satisfies certain conditions at the particular frequencies of interest.

At critical frequencies, f_0, f_1, etc.,

$$z_{1k} = \pm i2R. \tag{56}$$

At frequencies of infinite attenuation, $f_{0\infty}$, $f_{1\infty}$, etc.,

$$z_{1k} = \pm \frac{i2R}{\sqrt{1 - g^2}}. \tag{57}$$

Every negative or positive branch of z_{1k} includes one each of these frequencies.

For those wave-filters with only internal transmitting bands the additional relation will be used which specifies the frequencies where all image impedances equal R and the series impedances become resonant. At these resonant frequencies, f_{1r}, f_{2r}, etc., in the transmitting bands

$$z_{1k} = 0. \tag{58}$$

We know that in a "constant k" wave-filter the transmitting bands include the frequencies at which the series impedance z_{1k} is resonant. Hence, to the four forms of impedance function for z_{1k}, as in (51) to (54), there correspond four groups of wave-filter classes as already mentioned. These groups were designated according to the general locations of their transmitting bands which obviously correspond to the locations of the resonant frequencies of z_{1k}. For this reason each wave-filter group and the corresponding impedance form of z_{1k} have the same number designation.

Group 1. Low-and-n Band Pass.

An application of the theorem for Form 1 with (56) and (57) gives immediately the desired relation (20)

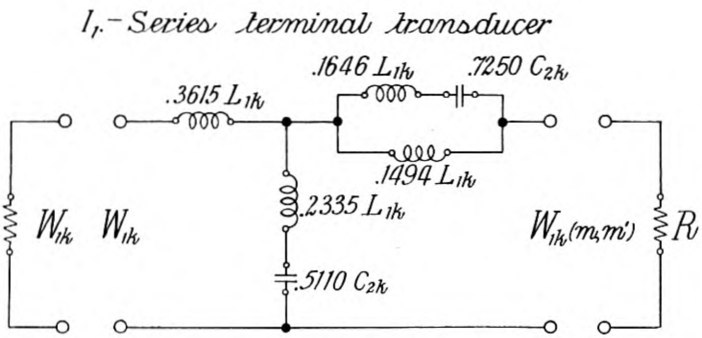
$$f_{0\infty} f_{1\infty} \cdots f_{2n\infty} = \frac{1}{\sqrt{1 - g^2}} f_0 f_1 \cdots f_{2n}.$$

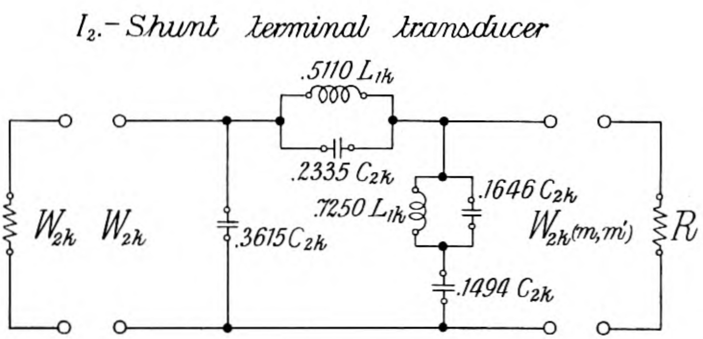
Similarly the relations (21), (22) and (23) are obtained for Groups 2, 3 and 4. Relation (24) for Group 4 is derived from (56) and (58), the latter corresponding to $c = 0$ in the theorem for Form 4 where each resonant frequency appears twice; the square root of the resulting relation is (24).

Appendix II

Fixed Terminal Transducers of Several Wave-Filter Classes

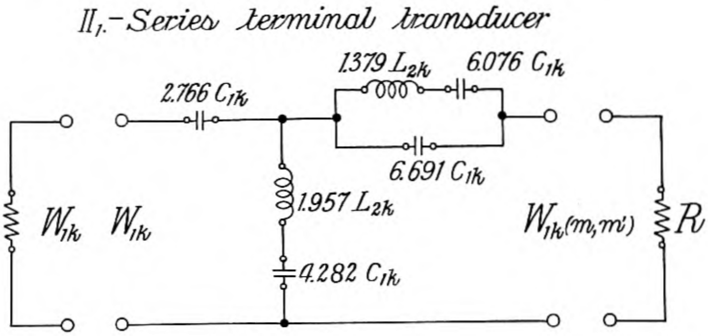
I. Low Pass.

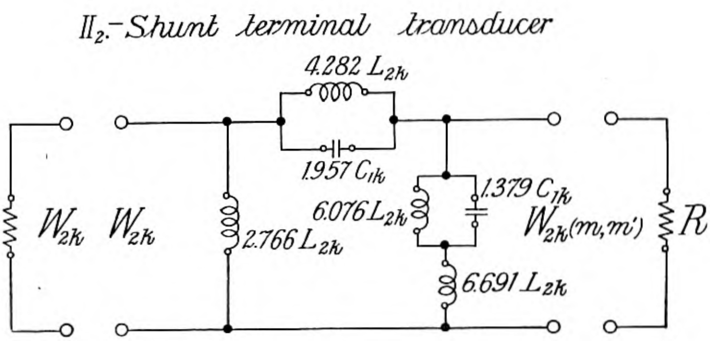




$$L_{1k} = \frac{R}{\pi f_0}, \qquad C_{2k} = \frac{1}{\pi f_0 R}\,.$$

II. High Pass.

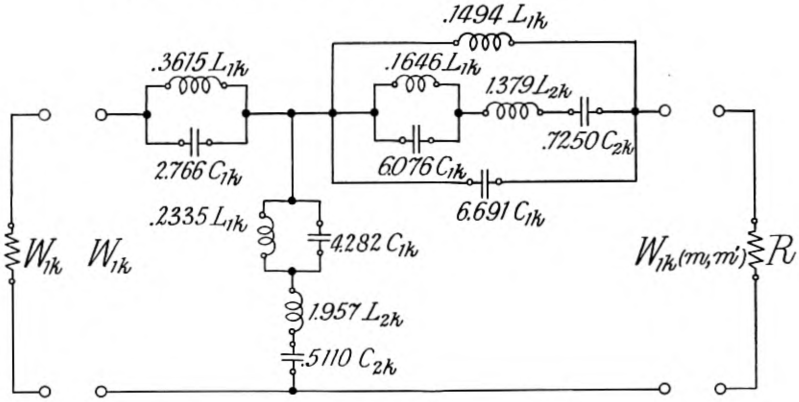




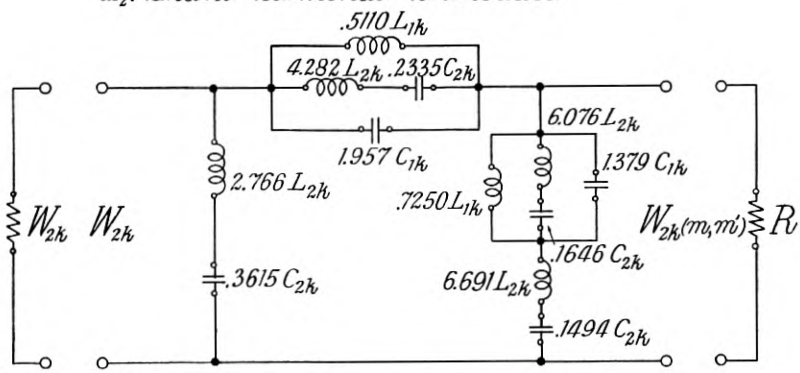
$$C_{1k} = \frac{1}{4\pi f_1 R}, \qquad L_{2k} = \frac{R}{4\pi f_1}.$$

III. Low-and-High Pass.

III_1.–Series terminal transducer



III_2.–Shunt terminal transducer

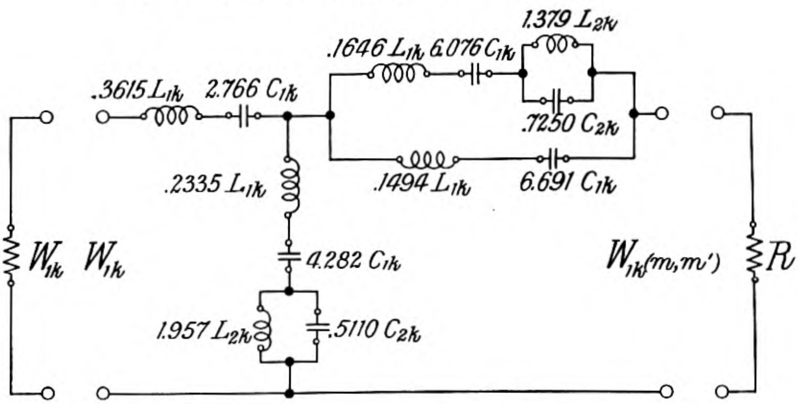


$$L_{1k} = \frac{(f_1 - f_0)R}{\pi f_0 f_1}, \qquad L_{2k} = \frac{R}{4\pi(f_1 - f_0)},$$

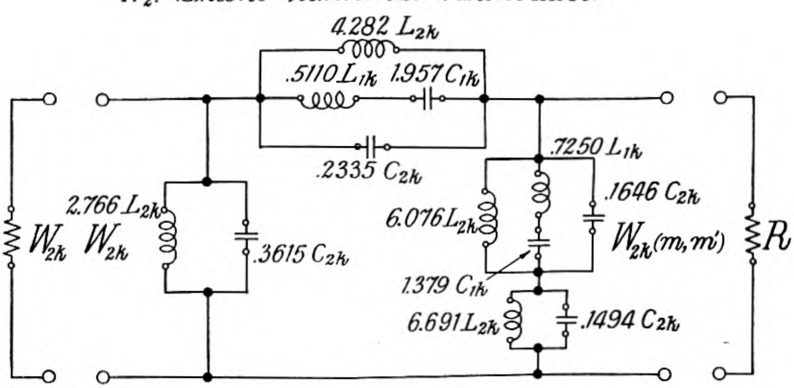
$$C_{1k} = \frac{1}{4\pi(f_1 - f_0)R}, \qquad C_{2k} = \frac{f_1 - f_0}{\pi f_0 f_1 R}.$$

IV. Band Pass.

IV_1.—Series terminal transducer



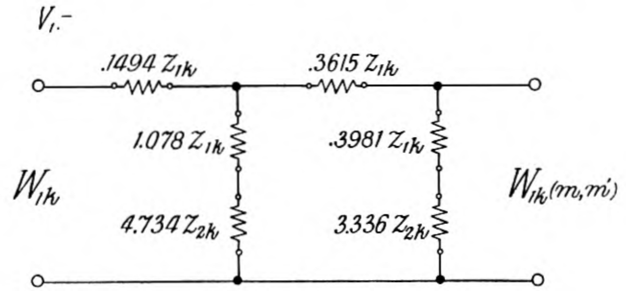
IV_2.—Shunt terminal transducer

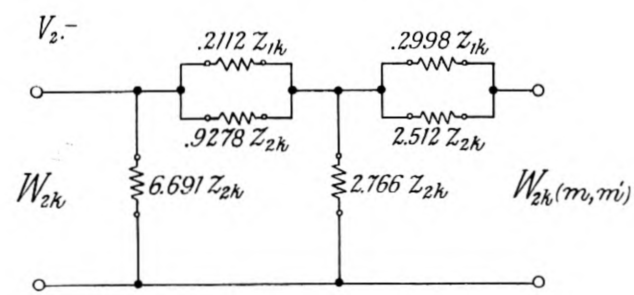


$$L_{1k} = \frac{R}{\pi(f_2 - f_1)}, \qquad L_{2k} = \frac{(f_2 - f_1)R}{4\pi f_1 f_2},$$

$$C_{1k} = \frac{f_2 - f_1}{4\pi f_1 f_2 R}, \qquad C_{2k} = \frac{1}{\pi(f_2 - f_1)R}.$$

V. Equivalents of Fixed Terminal Transducers of Fig. 11.

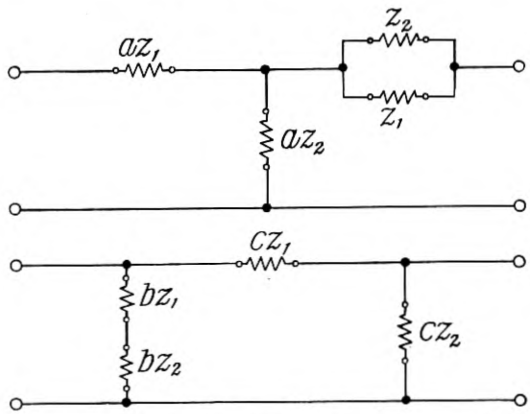




Appendix III

Equivalent Transducers and Transformation Formulas [16]

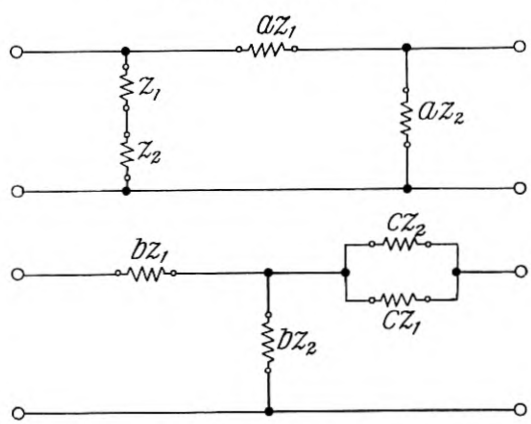
Transformation 1



Equivalent when

$$b = a(1 + a), \qquad c = 1 + a.$$

Transformation 2



Equivalent when

$$b = \frac{a}{1 + a}, \qquad c = \frac{a^2}{1 + a}.$$

[16] For transformations of simple equivalent two-terminal or impedance networks containing two kinds of general impedances, see Appendix III of paper in footnote 1. Also U. S. Patent No. 1,644,004 to O. J. Zobel, dated October 4, 1927.

Terminal Losses at Fixed MM'-Type Terminations

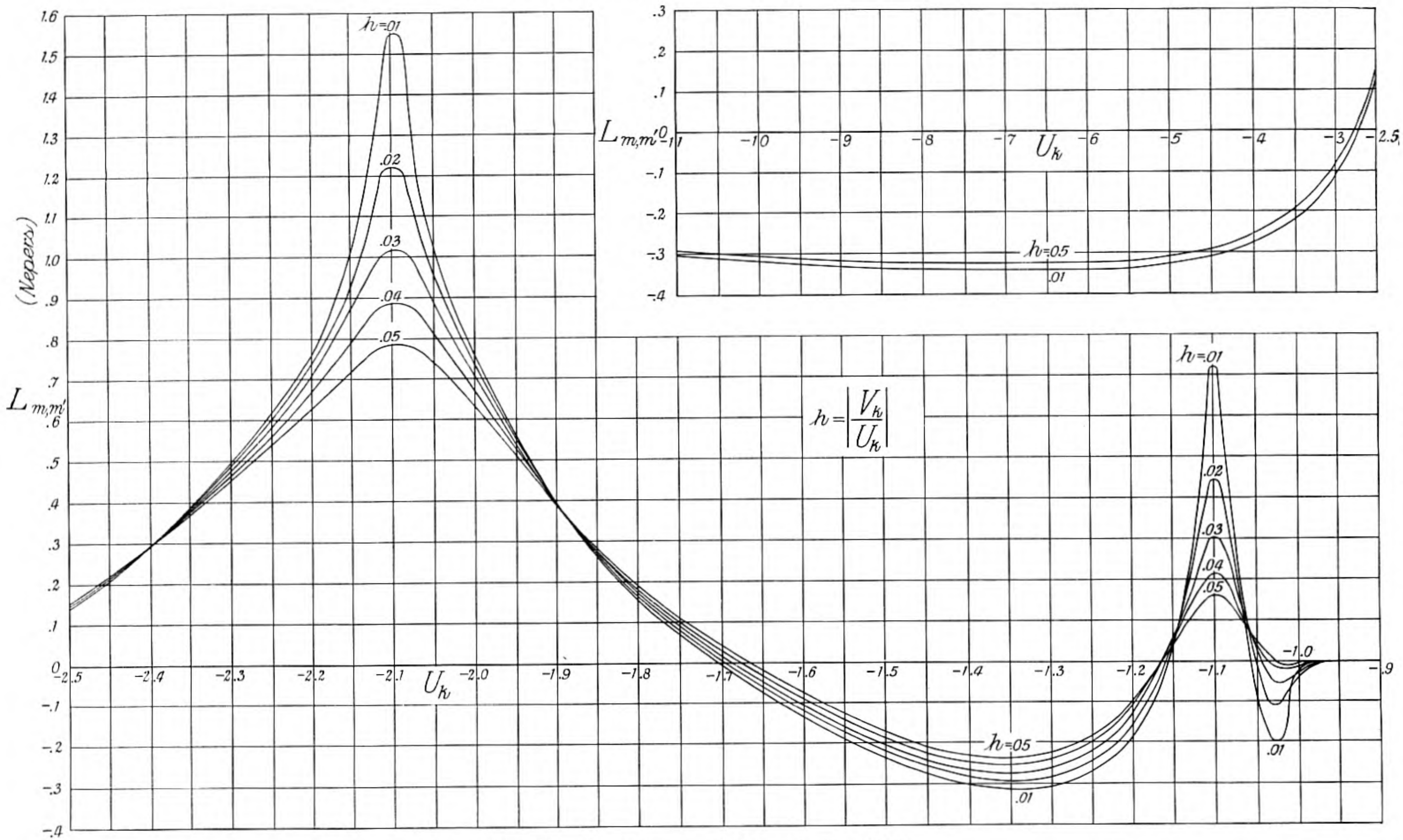


Chart 20.—$L_{m,m'}$ for m = .7230 and m' = .4134.

Abstracts of Technical Articles From Bell System Sources.

Western Electric Remodels Power Plant at Hawthorne Works.[1] C. B. Barnes. The summary of a six-year revamping program. A feature of the new plant is the installation of the largest cooling towers in America. Airplane propeller-type forced-draft fans are employed.

Long Telephone Lines in Canada.[2] J. L. Clarke. This paper describes the development of the long distance telephone service in Canada, historically, from its inception and the installation of the nucleus of 360 miles, up to and through the present status and lines listed in Table I, to the proposed development represented by Table II, the result of a careful study of calls per day to be expected by 1932. This effort is to provide for traffic requirements in a manner most suitable from a transmission point of view, and to accomplish it with a minimum amount of switching. Much of the engineering work for this is already actively under way and certain work of construction actually commenced. A survey of existing routes and the matter of transmission maintenance are discussed.

The "Raman Effect."[3] C. J. Davisson. A brief and informatory account of the "Raman Effect." For this new discovery in the realm of light and spectra, appraised as one of the most important achievements in physics in recent years, Sir C. V. Raman of India was awarded the Nobel Prize in physics for 1930.

Planning a Plant for the Manufacture of Lead-Covered Telephone Cable.[4] J. C. Hanley. Results of a study to determine the size and type of building to be erected, the arrangement of machinery for the most direct handling of product during process of manufacture, and the most efficient materials-handling equipment.

Outdoor Atmospheric Corrosion of Zinc and Cadmium Electrodeposited Coatings on Iron and Steel.[5] C. L. Hippensteel and C. W. Borgmann. Experimental data are presented on the rates of corrosion of electroplated zinc, zinc alloy and cadmium protective coatings on steel in a

[1] *Power*, Dec. 2, 1930.
[2] *Jour. A. I. E. E.*, Dec., 1930.
[3] *Sci. Monthly*, March, 1931.
[4] *Mech. Engg.*, March, 1931.
[5] *Trans. Amer. Electrochemical Soc.*, Vol. LVIII, 1930.

severely industrial atmosphere, and in a similar atmosphere, but accelerated by additional rainfall simulated by a water spray. These data show that zinc and zinc alloy coatings corrode at a slower rate than cadmium coatings. However, under the accelerated exposure the difference is not so pronounced.

Television in Color from Motion Picture Film.[6] HERBERT E. IVES. In speculations on the possible uses for television, one project which receives considerable attention, partly because of its relative ease of accomplishment, is the transmission of images from motion picture film. It is true that the practical simultaneity of event and viewing, which is the unique offering of television, is lost when the time necessary for photographic development of the film intervenes. Nevertheless, it is conceivable that if this delay is small, television from film may still possess such an advantage over the material transportation of film as to give it a real field. A further possibility, more remote, but within the range of legitimate speculation, is that television apparatus may sometime be used to receive, in the home, motion pictures of the sort now offered in the theatres or in home projection outfits. However distant these mergings of the two arts may be, the technical problems presented are pretty clearly defined, and offer interesting features for study.

Among these problems, and perhaps the farthest cry of any, is the transmission of images in color from colored motion picture film. This paper describes a method of accomplishing this, using the receiving apparatus for television in color recently described, and special sending apparatus which utilizes the latest form of colored moving pictures —the ridged film now marketed under the name of Kodacolor.

Private-Wire Telegraph Service.[7] R. E. PIERCE. An important part of the entire communication service of the United States is devoted to private wire service. More than one and one-half million miles of private wire telegraph service is furnished to press associations, brokers, financial houses, public service companies, and other organizations and individuals. Some of the interesting features involved are described here.

Absolute Amplitudes and Spectra of Certain Musical Instruments and Orchestras.[8] L. J. SIVIAN, H. K. DUNN, and S. D. WHITE. In a paper on "Speech Power and its Measurement," one of the authors has given some measurements of average and peak amplitude in speech,

[6] *Jour. Op. Soc. Amer.*, Jan., 1931.
[7] *Elec. Engg.*, Jan., 1931.
[8] *Jour. Acous. Soc. Amer.*, Jan., 1931.

using apparatus in which the speech spectrum was divided into thirteen bands of frequencies. The same apparatus has been used in a series of measurements on musical instruments, which are reported in this paper.

As with the speech measurements, the data are statistical in nature, and are taken with a view to their engineering applications. These applications are concerned, chiefly, with the transmission and reproduction of music, and the data should show the power and frequency requirements for systems which are called upon to perform these functions without distortion. In carrying out this purpose it has been thought well to measure both individual instruments, and instruments playing together in orchestras; to make measurements on actual musical selections, rather than on single notes; and to take the measurements in such a way as to obtain an average or integrated picture of the selection, as well as the distribution of amplitudes in magnitude and frequency, the extreme values being particularly important.

Noise Measurements.[9] JOHN C. STEINBERG. That noises have a detrimental effect upon human health and happiness has been proved and now efforts are under way to control or eliminate objectionable sounds. Some of the problems involved are outlined and a newly developed "noise meter" is described.

Fatigue Studies of Telephone Cable Sheath Alloys.[10] J. R. TOWNSEND and C. H. GREENALL. This paper is a continuation of a previous paper presented before the Society by one of the authors in 1927 and further discusses results of fatigue studies of lead sheath for telephone cables. The results of the investigation of the fatigue characteristics of lead cable sheath alloys, using the rotating-beam type fatigue machine, are reported. Data are also given for static fatigue.

The failure of lead cable sheath alloys as reported in the previous paper is by intergranular fracture and in the case of the lead-antimony alloys repeated stress appears to reduce the solubility of antimony in lead. The type of fracture observed for the rotating beam specimens is similar to that of the repeated flexure specimens described in the previous paper. The type of failure on the static fatigue test is a breaking down of the bond between the crystals.

The fatigue properties of the 0.04-per cent calcium-lead alloy described in this paper are by intergranular fracture, but there is no loss of solid solubility of the calcium in the lead. Great improvement in

[9] *Elec. Engg.*, Jan., 1931.
[10] *Proc. Amer. Soc. for Testing Materials*, Vol. 30, Part II, 1930.

the fatigue endurance was noted for an alloy of the same tensile properties as the lead-antimony alloy.

A Cooperative Electrolysis Survey in Louisville, Kentucky.[1] W. C. WHITE. A cooperative electrolysis survey in the city of Louisville, Kentucky, under the direction of an electrolysis committee is described. An analysis of a portion of the survey data and indicated mitigation measures are given as typical examples. The advantages of cooperative action in a general electrolysis survey are shown.

[1] *Elec. Engg.*, Feb., 1931.

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